AIR FORCE SPACE COMMAND

Volume 4, Number 3

HIGH FRONTIER

THE JOURNAL FOR SPACE & MISSILE PROFESSIONALS

INSIDE:

NGA: GPS Consumer and Contributor

Promoting International Civil GNSS Cooperation Through Diplomacy

Military Positioning, Navigation, and Timing: Strategic Challenges and Opportunities

Prepared Statement by General C. Robert Kehler

SPACE-BASED POSITIONING, NAVIGATION, AND TIMING

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **High Frontier, The Journal for Space & Missile Professionals. Volume 4, Number 3, May 2008**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Space Command (AFSPC),150 Vandenberg St. Ste 1105,Petereson AFB,CO,80914**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**64**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

HIGH FRONTIER

The Journal for Space & Missile Professionals

May 2008 — Volume 4, Number 3

Contents

Introduction

General C. Robert Kehler 2

Senior Leader Perspective

NGA: GPS Consumer and Contributor
VADM Robert B. Murrett 3

The National Coordination Office for Space-Based Positioning, Navigation, and Timing
Mr. Michael E. Shaw and Mr. Edward M. Morris 5

Senior Leader Profile

GPS On and Off the Battlefield: An Interview with Brig Gen John E. Hyten
Mr. Edward T. White 9

Industry Perspective

GPS Modernization and the Path Forward: Bringing New Capabilities to Military and Civil Users Worldwide
Dr. Donald G. DeGryse. 15

GPS Integral to SpaceX Falcon Launch Vehicles and Dragon Spacecraft
Mr. Eric L. Hultgren and Mr. Nicholas S. Blackwell 18

Space-Based Positioning, Navigation, and Timing

The International Committee on Global Navigation Satellite Systems: Building a System of Systems for a Global World
Ms. Sharafat Gadimova and Mr. Hans J. Haubold 22

Promoting International Civil GNSS Cooperation Through Diplomacy
Ms. Alice A. Wong and Mr. Ray E. Clore 25

Global Positioning Systems: Space-Based PNT for Today and Tomorrow
Col Donald E. Wussler, Jr. 28

Military Positioning, Navigation, and Timing: Strategic Challenges and Opportunities
Lt Col Jon M. Anderson 32

Controlling GPS: Architecture Evolution Plan and Beyond
Lt Col Harold W. Martin and Mr. Walter Petrofksi 38

GPS: Mission Success through Responsive Spacecraft Processing
Lt Col John Wagner, Mr. George Houser, and Mr. Don Skinner 42

The 2nd Space Operations Squadron Transforming Operations
Maj Michael A. Taraborelli 47

Worldwide Influence of GPS and the Challenges Ahead
TSgt Teresa A. Medlock 50

Historical Perspective

Tracing Connections—Vanguard to NAVSPASUR to GPS: An Interview with Roger Lee Easton, Sr.
Dr. Rick W. Sturdevant. 52

Congressional Testimony

Prepared Statement by General C. Robert Kehler 56

Book Review

GNSS—Global Navigation Satellite Systems: GPS, GLONASS, Galileo, and more
Dr. Rick W. Sturdevant. 62

Next Issue: ***National Security Space Collaboration***

Published by a private firm in no way connected with the US Air Force, under exclusive written contract with Air Force Space Command. This command funded Air Force journal is an authorized publication for members of the United States military Services. The views and opinions expressed in this journal are those of the authors alone and do not necessarily reflect those of the United States Department of Defense, the United States Air Force, or any other government agency.

Editorial content is edited, prepared, and provided by the *High Frontier* staff. All photographs are Air Force photographs unless otherwise indicated.

High Frontier, Air Force Space Command's space professional journal, is published quarterly. The journal provides a scholarly forum for professionals to exchange knowledge and ideas on space-related issues throughout the space community. The journal focuses primarily on Air Force and Department of Defense space programs; however, the *High Frontier* staff welcomes submissions from within the space community. Comments, inquiries, and article submissions should be sent to AFSPC.PAI@peterson.af.mil. They can also be mailed to:

AFSPC/PA
150 Vandenberg St. Ste 1105
Peterson AFB, CO 80914
Telephone: (719) 554-3731
Fax: (719) 554-6013

For more information on space professional development please visit:
http://www.afspc.af.mil

To subscribe:
Hard copy: nsage@colsa.com
Digital copy: http://www.af.mil/subscribe

Cover: (Top Left, Clockwise) F-15E Strike Eagle; Navstar Constellation: GPS Block IIA, IIR/M, IIF; SA Talanna Fisher, Schriever AFB, Colorado; farmland/GPS; Marine Sgt Brandon Shofne radios into headquarters descriptions of the ordnance found during a weapon cache sweep in Kharma, Iraq; GPS monitor, 22 SOPS.
Courtesy: A1C Jonathan Snyder, A1C Mark R. W. Orders-Woempner; AFSPC, Duncan Wood; Lance Cpl Matthew Hutchison

Back Cover: 2004/2005 imagery - tactical satellite (TACSAT).
Courtesy: STK graphic courtesy of Analytical Graphics, Inc.

Introduction

General C. Robert Kehler
Commander, Air Force Space Command

"With space systems, we use the ultimate high ground to persistently and precisely communicate, sense, and navigate anywhere on—or above—the globe."
~ Honorable Michael W. Wynne, secretary of the Air Force

Inside this quarter's *High Frontier* you will discover international perspectives, tactical-level paradigm shifts, *High Frontier's* first-ever senior leader interview, and a transcript of my testimony to the Senate Armed Services Committee. Air Force Space Command (AFSPC) delivers capabilities that transcend national and military boundaries and that are intrinsically and simultaneously both tactical and strategic, local and global. The Global Positioning System (GPS) provides multiple military benefits as well as a free international utility. Contemporary American warfare is based on global vigilance, reach, and power. Space-based positioning, navigation, and timing (PNT) capabilities afforded by GPS, enhance the effectiveness of America's joint forces by enabling delivery of swift and precise effects which provide overwhelming and decisive results with minimum collateral damage.

Leading off the "Senior Leader Perspective" section, Vice Admiral Robert B. Murret, USN, director, National Geospatial Intelligence Agency, gives an inside look at how GPS provides actionable geospatial intelligence to deployed forces. Next, Mr. Michael Shaw and Mr. Edward Morris highlight how the National Coordination Office carries out the US National policy for PNT and how it provides guidance to government agencies on the management of GPS and other space-based PNT systems. Lastly, in our "Senior Leader Profile," Brigadier General John Hyten, AFSPC's director of requirements, discusses current and future GPS system requirements.

Opening the "Industry Perspective" section, Dr. Donald DeGryse, from Lockheed Martin, discusses how the Air Force establishes a next-generation GPS program by incrementally increasing capabilities to meet current and future needs. Next, Mr. Eric Hultgren and Mr. Nicholas Blackwell of SpaceX, describe their plans for reusable launch vehicles and how they utilize GPS signals during ascent, orbital navigation and recovery operations.

Moving through the bulk of this quarter's volume, we provide seven articles with topics spanning from international partnerships to unit-level tactical employment. In the first article, 'The International Committee on Global Navigation Satellite Systems' (GNSS), Ms. Sharafa Gadimova and Mr. Hans J. Haubold, programme officers for the United Nations Office for Outer Space Affairs, Vienna Australia, outline how in 2005, the United Nations established the GNSS to ensure compatibility and system interoperability, thereby saving costs through international cooperation and making PNT services available for societal benefits. The second article by Ms. Alice Wong, senior advisor for GPS Issues, Office of Space and Advanced Technology, Bureau of Oceans, Environment and Science (OES) and Mr. Ray Clore, senior advisor for GPS-Galileo Issues, OES, give a summary of US diplomatic efforts in support of compatibility and interoperability among current and future space-based PNT systems. Next Col Donald Wussler the vice commander at the GPS Systems Wing, Space and Missile Systems Center, elaborates on all aspects of GPS PNT development, sustainment, and services. He highlights the influence space-based PNT has on the military, civilian, and international communities, to include future technical, leadership, and strategic challenges. Expanding on PNT strategic challenges Lt Col Jon Anderson a student at Naval War College, discusses near term PNT capability gaps and how to ensure the US remains ahead of the pack in military PNT. Addressing future command and control is Lt Col Harold Martin the AFSPC command lead for PNT and Mr. Walter Petrofski from SI International. Next, Lt Col John Wagner the commander of the 45th Space Wing's launch Support Squadron, details the integrated contractor-government team approach employed by the GPS program and how it has become a model for responsive spacecraft processing. The final two articles move us closer to the pointy end of the spear. First, Maj Michael Taraborelli, 2nd Space Operations Squadron (2 SOPS), provides a glimpse into how 2 SOPS is shifting its tactical operations paradigm to increase interaction across the acquisitions, operations, and sustainment communities. Rounding out the "Space-Based PNT" section, TSgt Theresa Medlock, 21st Operations Support Squadron, tackles the challenges brought about by the world-wide influence of GPS and concludes with recommendations for GPS's continued success.

In the "Historical Perspective" section, we present an intriguing interview with Mr. Roger Easton, who received the National Medal of Technology from President George W. Bush on 13 February 2006, for his many pioneering achievements in tracking, navigation, and timing which led to GPS. Lastly, I have included a transcript of the prepared statement I presented to the Senate Armed Services Committee, Strategic Forces Subcommittee, United States Senate, on the 4th of March 2008. The testimony highlights the important role the AFSPC team plays in delivering space and missile capabilities to America and its warfighting commands. We cannot underestimate the importance of Congressional support as we realize our vision of delivering responsive, assured, and decisive space power.

I hope you enjoy this and future issues of *High Frontier* and use them as part of your own space professional development regimen. The subject of our next issue is National Security Space Collaboration. I encourage you to submit articles that spur discussion by illustrating the impacts, integration issues, and future challenges of our classified and unclassified space missions.

General C. Robert "Bob" Kehler (BS, Education, Pennsylvania State University; MS, Public Administration, University of Oklahoma; MA, National Security and Strategic Studies, Naval War College, Newport, Rhode Island) is commander, Air Force Space Command (AFSPC), Peterson AFB, Colorado. He is responsible for the development, acquisition, and operation of the Air Force's space and missile systems. The general oversees a global network of satellite command and control, communications, missile warning and launch facilities, and ensures the combat readiness of America's intercontinental ballistic missile force. He leads more than 39,700 space professionals who provide combat forces and capabilities to North American Aerospace Defense Command and US Strategic Command (USSTRATCOM).

General Kehler has commanded at the squadron, group, and twice at the wing level, and has a broad range of operational and command tours in ICBM operations, space launch, space operations, missile warning, and space control. The general has served on the AFSPC Staff, Air Staff, and Joint Staff and served as the director of the National Security Space Office. Prior to assuming his current position, General Kehler was the deputy commander, USSTRATCOM, where he helped provide the president and secretary of defense with a broad range of strategic capabilities and options for the joint warfighter through several diverse mission areas, including space operations, integrated missile defense, computer network operations, and global strike.

NGA: GPS Consumer and Contributor

VADM Robert B. Murrett, USN
Director, National Geospatial Intelligence Agency
Bethesda, Maryland

Over the past decade, the NAVSTAR Global Positioning System (GPS), managed by the United States Air Force Space Command for the Department of Defense (DoD), has become the most exploited space-based asset the US government ever developed. Since GPS provides space-based radio navigation for anyone with a GPS receiver, both military and civilian uses have increased exponentially.

In fact, everything geospatially oriented today is reliant on GPS. Most military and intelligence operations depend on knowing precisely where something is located. National Geospatial Intelligence Agency's (NGA's) mission is to provide accurate, timely and actionable geospatial intelligence (GEOINT) to our mission partners, when and where they need it most. From the warfighter on the front line to the local search and rescue team seeking flood victims, NGA provides GEOINT to support operational and decision-making needs.

For example, NGA provides the geospatial products that enable warfighters—Soldiers, Sailors, and Airmen—to accurately locate and hit targets. NGA analysts build a picture for the warfighter by layering natural features, such as rivers, hills, and waterways, with man-made features, such as roads, power lines, and buildings to develop a two-dimensional or three-dimensional (3-D) picture for common use. Knowing that a target of interest exists is important; knowing where exactly that target of interest is located ensures accurate targeting and minimizes the risk of collateral damage. To target an object, the warfighter needs accurate geographic coordinates. Subsequently, each data layer used in the development of a GEOINT product is referenced to a standard coordinate system.

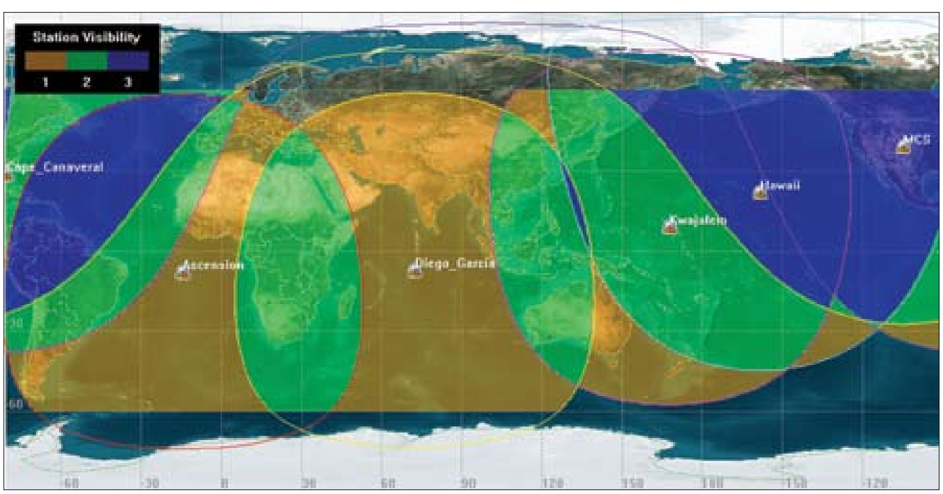


Figure 1. GPS Satellite Integrity Monitoring—Satellite Visibility from Tracking Stations. Stations in View, 6 USAF Stations.

Ensuring Accuracy and Reliability

US national security, transportation, navigation safety, economic interests, and scientific uses all rely on GPS. This increasing dependence demands that the coordinate information and reference system be both accurate and accessible. NGA plays an essential role in maintaining and improving the accuracy and reliability of GPS by providing the DoD with precise GPS orbits, satellite and station clock corrections, and Earth orientation information. NGA is not only a daily consumer of GPS but a robust contributor as well.

NGA and its predecessor organizations partnered with the DoD to develop the World Geodetic System 1984 (WGS 84) as the standard geodetic frame of reference. The WGS 84 global reference frame provides a mathematical representation of the Earth's shape, a 3-D coordinate system, and a gravity model which is essential for computing satellite orbits and precise locations on, above or below the Earth's surface. WGS 84 provides a common, standardized reference frame for inter-relating and integrating all geospatial data, including GPS-derived position information. This global reference information is what allows users to determine their locations on Earth based on the precise positions of GPS satellites in space.

Prior to the 1950s, coordinate systems were developed regionally. Once satellites became available in the 1950s and 1960s, NGA was able to establish an Earth-centered, global coordinate system. Today, the WGS 84 coordinate system, used by GPS, is defined by the 3-D coordinates established by the combination of the Air Force and NGA satellite tracking stations distributed around the world. The more accurately NGA knows the positions of these tracking stations, the more accurately NGA can determine the GPS satellite positions. Currently, NGA estimates the accuracy of these station coordinates within a few centimeters or less. As a by-product of this data processing, NGA can also detect small variations in the Earth's orientation in space and its rotation rate. This information is crucial for the accurate and precise orientation and geopositioning of satellite imagery.

Precise timing is the key to GPS's accuracy. Every DoD GPS tracking station and GPS satellite is equipped with an atomic clock, each of which runs at slightly different rates. NGA co-located a tracking station with our nation's master time keepers at the US Naval Observatory (USNO) in Washington, DC. This allows NGA to take advantage of the stability, precision and accuracy of the USNO time by defining it as the GPS "master clock," and then to adjust all the other satellite and station clocks to the master.

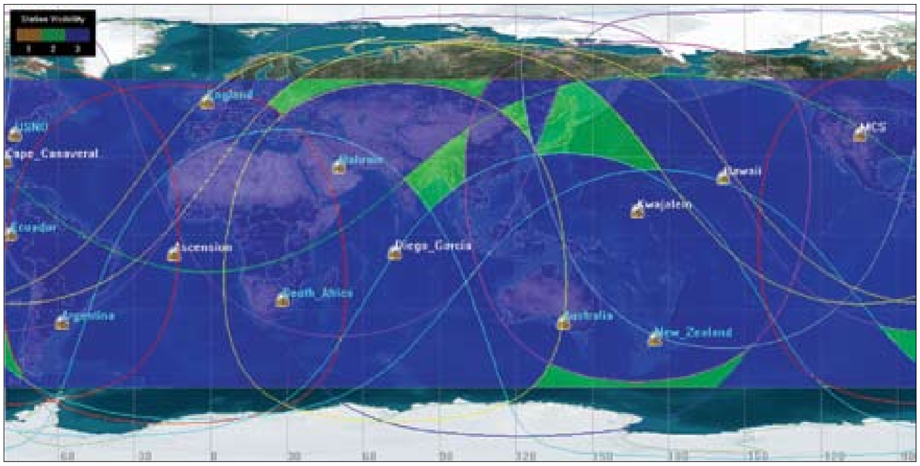


Figure 2. GPS Satellite Integrity Monitoring—Satellite Visibility from Tracking Stations. 8 NGA + 6 USAF Stations.

Reliability of service is essential to GPS effectiveness. Beginning in the 1980s, NGA provided personnel support at the GPS Joint Program Office (now the GPS Wing) at Los Angeles AFB, California and the Operational Control Station (OCS) at Schriever AFB, Colorado. Additionally, NGA invested in building and operating a global network of unmanned GPS tracking stations to augment the Air Force's permanent GPS tracking stations. The result has been substantial benefits to the entire GPS user community. As part of a major accuracy improvement initiative, NGA stations now feed real-time data to the GPS through the OCS at Schriever AFB. These data are incorporated into the real-time estimation process for GPS orbit determination, resulting in increased accuracy and integrity of GPS navigation signals for GPS users.

Looking Forward

Future improvements and maintenance of GPS augmentations and back-up capabilities are necessary to meet growing national security, economic, commercial, and scientific requirements and opportunities. For example, new foreign-based Global Navigation Satellite Systems (GNSS), such as Russia's GLONASS and Europe's Galileo System, provide additional options for current and future GPS users. These foreign systems are not yet as robust as the GPS system, but may be in future years. With ongoing efforts to assure interoperability among all the systems, every system may be vulnerable to the same intentional or unintentional interference. The shear number of combined GNSS satellites, upwards of 60 to 100 in the future, may help to mitigate these effects. The defense community is exploring new mitigation strategies to counter electromagnetic radiation interference caused by solar flares or geomagnetic storms, as well as intentional and unintentional radio jamming caused by man-made techniques. DoD's development and implementation of a military-only code (M-code) and other new satellite features are designed to protect and preserve US strategic access to GPS, even in hostile environments.

As we look toward the future and the next evolution of GPS, we must ensure interoperability and compatibility in the context of geospatial information. NGA will continue its strong collaboration with the US Air Force to ensure future satellite procurement and technological decisions consider geospatial intelligence needs and capabilities. Additionally, NGA's continued participation in the International GNSS Service, the international organization that produces state-of-the-art GNSS data and products for the scientific community, will also help ensure that NGA stays up-to-date on the latest GNSS science and technology.

As both a consumer and a contributor of GPS, NGA is committed to integrating and working collaboratively with our mission partners as we make the best decisions to ensure our national security, safety, and stability.

VADM Robert B. Murrett (BA, History, University of Buffalo; MA, Government, Georgetown University; MS, Strategic Intelligence, Defense Intelligence College) is the director of the National Geospatial-Intelligence Agency (NGA). He is responsible for providing timely, relevant and accurate geospatial intelligence in support of policy makers and the warfighter. He manages NGA with employees located around the world in support of global operations.

Following his commission, Admiral Murrett was assigned as an intelligence officer aboard USS KITTY HAWK (CV 63), USS AMERICA (CV 66), and USS INDEPENDENCE (CV 62). After attending the Defense Intelligence College, Admiral Murrett was detailed to the chief of Naval Operations Intelligence Plot as a watch stander and briefing officer for Navy civilian and military leaders. He served as assistant intelligence officer for commander, Second Fleet. He participated in deployments to the North Atlantic, the European theater and Caribbean aboard USS MOUNT WHITNEY (LCC 20) and USS NASSAU (LHA 4). Admiral Murrett served as the assistant naval attaché to the US Embassy in Oslo, Norway.

Admiral Murrett was assigned as operational intelligence officer for the commander in chief, US Pacific Fleet. He served as assistant chief of staff, intelligence for Commander Carrier Group Eight and deployed aboard USS THEODORE ROOSEVELT (CVN 71) to European and Central Command theaters. He was also assigned as J2 for CJTF 120 and as N2 for NATO's Striking Fleet Atlantic. Next, he was assigned to the Chief of Naval Operations Staff as executive assistant to the director of Naval Intelligence, then director, Intelligence Directorate, Office of Naval Intelligence. In 1999, the admiral assumed the duties of commander, Atlantic Intelligence Command (AIC) where he was responsible for the transition of AIC to Joint Forces Intelligence Command of which he later became the director for intelligence. Admiral Murrett was the vice director for intelligence, J2, on the Joint Staff. Prior to joining NGA in July 2007, Admiral Murrett served as the director of Naval Intelligence.

Senior Leader Perspective

The National Coordination Office for Space-Based Positioning, Navigation, and Timing

Mr. Michael E. Shaw
Director, National Coordination Office for Space-Based Positioning, Navigation, and Timing
Washington DC

Mr. Edward M. Morris
Director, Office of Space Commercialization
National Oceanic and Atmospheric Administration
US Department of Commerce
Washington DC

SPACE-BASED POSITIONING NAVIGATION & TIMING
NATIONAL COORDINATION OFFICE

In December 2004, President George W. Bush issued the US Policy on space-based positioning, navigation, and timing (PNT), providing guidance to government agencies on the management of the Global Positioning System (GPS) and other space-based PNT systems. The policy established the National Executive Committee (EXCOM) for space-based PNT to advise and coordinate federal agencies on matters related to space-based PNT. Chaired jointly by the deputy secretaries of defense and transportation, the EXCOM includes equivalent-level officials from the Departments of State, the Interior, Agriculture, Commerce, and Homeland Security, the Joint Chiefs of Staff, and the National Aeronautics and Space Administration (NASA). A National Coordination Office (NCO) supports the EXCOM through an interagency staff provided by the EXCOM member agencies.

The Department of Commerce (DoC) played an instrumental role in establishing the EXCOM and NCO in 2005. Since then, the organizations have quickly grown in influence and effectiveness, leading or managing many interagency initiatives. These include the development of a five-year national plan for space-based PNT, the Space-Based PNT Interference Detection and Mitigation Plan, and other strategic documents. The NCO has also facilitated interagency coordination on numerous policy issues and on external communications intended to spread a consistent, positive US message about space-based PNT. The success of the EXCOM and NCO has yielded collateral benefits for DoC, which closely associates with these interagency bodies as their physical and institutional home.

Mr. Michael E. Shaw speaking on behalf of the National Coordination Office for Space-Based PNT, Location Asia 2007 conference, Hong Kong, September 2007.

Establishing the NCO at DoC

In 2005, the EXCOM co-chairs accepted an offer from then–Deputy Secretary of Commerce David Sampson to host the NCO at the DoC building in Washington, DC. Aside from being conveniently accessible to the interagency community, DoC represented a "neutral ground" for resolving contentious issues. Placing the NCO—and by extension, the EXCOM—at DoC also demonstrated to the world that the US government treats GPS as a national asset, not just a military system, without shifting too much weight to the civil co-chair. Finally, putting DoC at the center of space-based PNT policy activities helped acknowledge the millions of commercial users, manufacturers, and service providers who comprise the largest constituency in the space-based PNT community.

As host of the EXCOM and NCO, DoC provides offices, meeting facilities, information technology, financial management, travel support, and other in-kind services. DoC's Office of Space Commercialization budgets for this logistical support and is authorized to accept interagency resources for NCO operations. In budgetary terms, the NCO represents a $3.5 million enterprise during fiscal year 2008, including funding contributions from the Departments of Defense (DoD) and Transportation (DoT) and nine personnel from the EXCOM agencies.

Role of the NCO

The purpose of the EXCOM is to provide top-level guidance to US agencies regarding space-based PNT infrastructure. The president established it at the deputy secretary level to ensure its strategic recommendations effect real change in agency budgets. Recognizing such high-level officials could only meet every few months, the president directed the EXCOM to establish

an NCO to carry out its day-to-day business.

The business includes a great deal more than preparing meeting agendas and minutes for the EXCOM. It also includes overseeing the implementation of dozens of action items assigned across the member agencies during EXCOM meetings. These range from the resolution of funding issues to the assessment of strategic policy options. They also include the completion of specific tasks and documents requested by the EXCOM co-chairs. A key function of the NCO is to track all the action items to ensure their timely execution.

One of the management tools the NCO uses to encourage progress on EXCOM action items is a "stoplight" chart of all open assignments, indicating status as green (on track), yellow (falling behind), or red (overdue). The NCO distributes this chart monthly to agency leadership and highlights problematic items at the EXCOM meetings.

Completing an action item often requires interagency coordination and/or dispute resolution. In such cases, the NCO serves as a facilitator seeking common ground among the interested parties. The NCO has established several processes for achieving interagency consensus on policy issues, including specialized staff-level working groups and an assistant secretary–level Executive Steering Group.

The NCO also established a process for interagency coordination of US government communications related to space-based PNT, including speeches, presentations, and other externally released documents. The goal is to ensure government-wide consistency and accuracy in public and international statements made about space-based PNT. This is particularly important in addressing false or misleading information about GPS in the public arena.

Five-Year National Plan for Space-Based PNT

The NCO is responsible for developing a five-year national plan for space-based PNT including program plans, schedules, and budgets for GPS and its augmentations. The president directed that this internal planning document be updated annually to ensure its relevance to agency budget preparations each year. In August 2007, the NCO completed the first edition of the plan after many months of data collection, analysis, and coordination. The document summarizes planning and identifies interagency program dependencies for the development, acquisition, deployment, operation, sustainment, and modernization of US space-based PNT systems.

As part of the process, the NCO reviewed the adequacy of agency budgets to support the timely delivery of US space-based PNT capabilities and services. A major focus of this effort was the need for non-DoD funding to support future, civil-unique GPS upgrades. The NCO brought the issue to the EXCOM for discussion and the issue was resolved in the fiscal year 2009 budget submission to Congress.

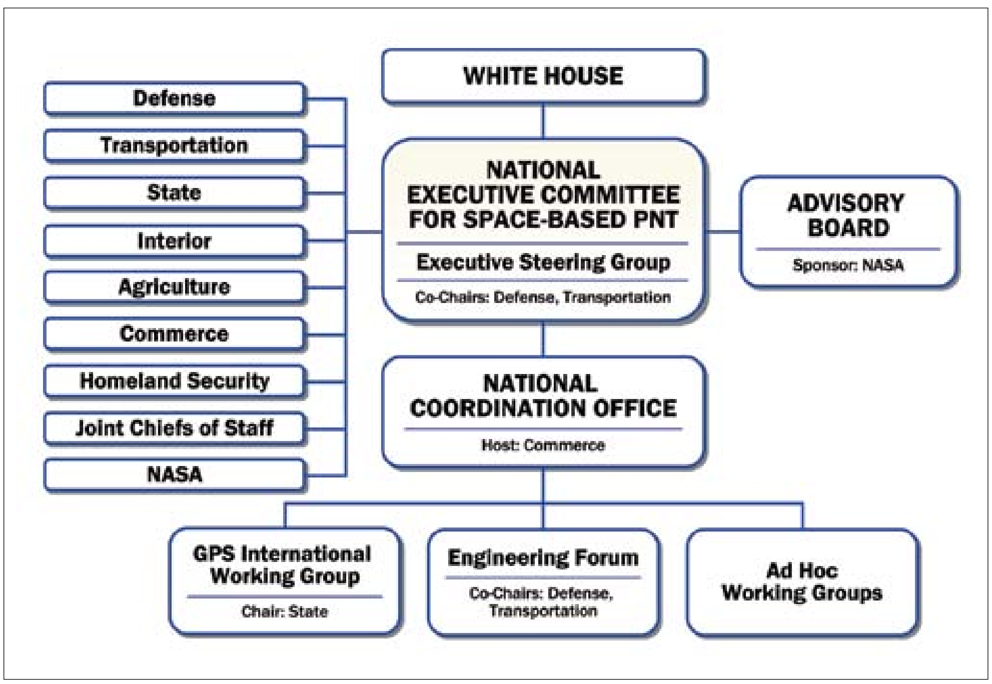
Space-Based PNT Interference Detection and Mitigation Plan

The president's space-based PNT policy directed the Department of Homeland Security (DHS) to develop a national plan for detecting and mitigating interference to US space-based PNT systems. The ability to respond to intentional and unintentional sources of radio interference is essential, as multiple sectors of the nation's critical infrastructure rely on GPS and its augmentations. The NCO played an important role in moving the plan forward and coordinating it among the EXCOM agencies prior to its submission to the president in 2007. Because the document describes vulnerabilities in US infrastructure, it is not publicly releasable. However, in April 2008, DHS released a public fact sheet and summary of the plan via the NCO Web site.

International Cooperation

The NCO works closely with the State Department to develop and coordinate strategies for international engagement and cooperation related to space-based PNT. Such strategies have assisted in establishing or continuing successful US cooperation with Europe's planned Galileo system, Russia's Global Navigation Satellite System (GLONASS), Japan's Quasi-Zenith Satellite System, and India's Regional Navigation Satellite System. The State Department's GPS International Working Group (GIWG), established in the early 1990s, now fits within the EXCOM's organizational framework.

The GIWG and NCO meet quarterly to plan upcoming outreach opportunities for US officials to deliver a coordinated and positive message about US space-based PNT programs and



National Space-Based PNT Organization Structure.

policies to international audiences. US representatives speak about space-based PNT at a variety of conferences, workshops, seminars, and other public engagements.

The NCO supports US participation in the International Committee on Global Navigation Satellite Systems (ICG), a United Nations–affiliated body promoting communication among global space-based PNT providers and users. The NCO contributes to US government funds supporting ICG operations, including regional workshops and seminars intended to teach developing countries how to use space-based PNT to improve quality of life.

Enhanced LORAN

In February 2008, DHS announced its decision to upgrade the US Coast Guard's aging Long Range Aids to Navigation (LORAN) system to become enhanced LORAN (eLORAN). Providing a national backup to GPS for PNT services was the basis for their decision. The decision followed recommendations from several groups, including the EXCOM, which reviewed the issue in early 2007 and unanimously endorsed the eLORAN concept. In the following months, the NCO played a key role in driving the US government toward a decision on eLORAN.

National Space-Based PNT Systems Engineering Forum

The NCO chartered the National Space-Based PNT Systems Engineering Forum (NPEF) in 2007 as a mechanism for engaging the collective expertise from multiple agencies on specific technical tasks related to space-based PNT. Such tasks include the investigation of GPS satellite anomalies that occurred following the transition of the operational control segment to a new, modernized architecture. The NPEF is a permanent working group under the NCO co-chaired by the DoD and DoT and including more than 11 agencies.

National PNT Architecture

In early 2006, the EXCOM directed the NCO to initiate an effort with the DoD's National Security Space Office (NSSO) to develop an overall US PNT architecture focused on the year 2025. The effort coincided with a study requested by the assistant secretary of defense for networks and information integration for the NSSO to develop a national PNT architecture.

In addition, the under secretary of transportation for policy tasked the DoT Research and Innovative Technology Administration to co-lead the national PNT architecture on behalf of the civil community. The intent is to arrive at a common vision for the future of PNT (space-based and otherwise) that will create an evolutionary path for government-provided PNT systems and services, provide direction for science and technology efforts and capital investment decisions, and identify and eliminate unnecessary infrastructure. The NCO participated as a member of the PNT architecture team, which included more than 200 participants from across the interagency community. The team spent 18 months assessing the detailed PNT landscape now and in the future, evaluating numerous potential contributing elements in the future PNT architecture, and developing strategies, vectors, and recommendations to realize that future architecture. The team's recommendations have been approved, and the team is now moving into the planning phase of the architecture process for the recommendations.

National Space-Based PNT Advisory Board

The president's policy calls for the establishment of a federal advisory committee comprised of experts from outside the US government to provide independent advice to the EXCOM. The NCO and NASA developed and coordinated the charter and initial membership of the National Space-Based PNT Advisory Board. As the official sponsor of the advisory board, NASA provides administrative support and collaborates with the NCO on meeting agendas and taskings to ensure direct support of the EXCOM mission. The EXCOM has tasked the board to develop recommendations related to US space-based PNT leadership, strategic engagement and communication, and future challenges. The board met twice in 2007 and last met 27-28 March 2008.

Outreach and Education

The NCO plays a central role distributing information to the world about US space-based PNT programs and policy. The NCO manages two public Web sites providing information about space-based PNT. The first, GPS.gov, focuses on worldwide uses of GPS. It is available in five languages—English, Spanish, French, Chinese, and Arabic—to reach a broad international audience. The NCO also printed the contents of the website as a 16-page color brochure distributed at global PNT conferences. The NCO's second Web site, PNT.gov, provides information about US space-based PNT policy and the activities of the EXCOM and NCO. The site contains copies of international cooperation agreements and public US presentations related to space-based PNT policy. DoC provides technical support to both sites and physically hosts the PNT.gov servers.

The NCO staff participates in a broad variety of conferences and other international outreach venues, including meetings of the International Civil Aviation Organization, Asia-Pacific Economic Cooperation, and the United Nations Committee on the Peaceful Uses of Outer Space. Other forms of outreach include organizing events and exhibits.

In early 2006, the NCO and DoC co-sponsored a media event at the US Chamber of Commerce celebrating the initial availability of the second civil signal (L2C), a new civilian signal launched as part of the GPS modernization program. The deputy secretary of commerce delivered the keynote address, crediting stable and transparent US policies for creating the multibillion industry in space-based PNT. DoC followed up by publishing an article quantifying the estimated productivity benefits of L2C at $5.8 billion during the next 30 years.

In 2007, the NCO contributed funds and other resources toward the development of a new public education exhibit called "GPS Adventures." This large-scale, immersive experience is designed to teach children and the general public about GPS technology through geocaching, a growing recreational activ-

ity. The exhibit is on display at the Minnetrista Cultural Center in Indiana, where it has broken attendance records. It will travel to several other US science museums, reaching thousands of Americans across the nation.

The Way Ahead

In 2007, the EXCOM co-chairs directed the NCO to identify open action items and unresolved issues for completion by the end of 2008 to enable a smooth transition to the next administration. The NCO worked closely with EXCOM member agencies to prioritize top short-term issues and compiled them into a comprehensive 2008 Work Plan. The work plan includes assignments for DoD to release an update to the GPS Standard Positioning Service Performance Standard; for DoT to decide the future of the Nationwide Differential GPS program; and for DHS to complete the Interference Detection and Mitigation implementation strategy. The NCO tasked itself to develop a 2009 transition book for the incoming EXCOM leadership. The NCO is tracking the progress of the 2008 Work Plan using the same stoplight chart process used for EXCOM action items.

An assignment for DoC in the 2008 Work Plan was to submit legislation to Congress that would help ensure the long-term sustainability of the NCO and EXCOM. In October 2007, the administration proposed a new bill intended to update the legal functions of DoC's Office of Space Commercialization. The legislation would codify the existing relationship between DoC and the national space-based PNT policy organizations. If passed, the bill would ensure the Office of Space Commercialization continues to support the NCO and EXCOM as one of its permanent responsibilities, regardless of future changes in political leadership. The legislation would also task the Office of Space Commercialization to promote advancement of US geospatial technologies, including space-based PNT.

The text of the proposed legislation is available at space.commerce.gov. As of the writing of this article, the bill did not have a number because its sponsor in Congress had not formally introduced it. DoC expects this to occur during spring 2008.

Conclusion

In less than three years, the NCO evolved from an idea into a highly active organization with substantial influence within the space-based PNT community. NCO efforts have helped build the EXCOM into an effective mechanism for raising issues to the attention of senior leadership and ensuring their guidance gets implemented. While it is still a work in progress, the NCO has many significant accomplishments.

The symbiotic relationship between the NCO and DoC provides mutual benefits for both parties. Going forward, this relationship will mature as ongoing US government space-based PNT activities continue bearing fruit and DoC's support to the NCO and EXCOM progresses from a political commitment to a legislative mandate.

Mr. Michael E. Shaw has served as director of the National Coordination Office since its inception in 2005. A member of the Senior Executive Service and former commander of the USAF squadron that operates the GPS constellation, Mr. Shaw brings many years of military and civil PNT experience to the job. He is responsible for carrying out the mission, objectives, and goals of the EXCOM in accordance with the US Space-Based PNT policy. In addition, he facilitates information sharing, coordination, and issue resolution regarding agency program plans, requirements, budgets, and policies for operation of US space-based PNT systems and services. Lastly, he represents the EXCOM on space-based PNT matters within the government, the public sector, and with representatives of foreign governments and international organizations.

Mr. Shaw previously held management positions related to Space-Based PNT policy in the Office of the Under Secretary of Transportation for Policy; the Office of the Assistant Secretary of Defense for Command, Control, Communication, and Intelligence; the Federal Aviation Administration; and the Office of the Assistant Secretary of the Air Force for Space. He participated in international negotiations involving GPS and its augmentations including the Wide Area Augmentation System, Local Area Augmentation System, and the Nationwide Differential GPS System.

Mr. Shaw was a career navigator in the Air Force, where he was a weapon systems officer in the F-4 Phantom aircraft. He served as director of operations, and later, commander of the 2nd Satellite Operations Squadron, responsible for the command, and control of the GPS satellite constellation.

Mr. Edward M. Morris (BS, Engineering, Rutgers University; MBA, Pepperdine University) is director, Office of Space Commercialization, National Oceanic and Atmospheric Administration, Department of Commerce. The office is responsible for implementing national space policies and promoting the capabilities of the US commercial space industry. It acts as an industry liaison within the Executive Branch to ensure the US government maximizes its use of commercially available space goods and services, avoids legal and regulatory impediments, and does not compete with the US space industry. The office also hosts the NCO and supports the deputy secretary of commerce on the EXCOM.

Mr. Morris is the US government co-chair of the GPS-Galileo Working Group on Trade and Civil Applications, responsible for addressing non-discrimination and other trade related issues concerning space-based PNT.

From 1991 to 2006, Mr. Morris worked for Orbital Sciences Corporation, most recently as senior director of Washington operations. He received the Outstanding Management Award in 2001 for achieving key business development goals.

Mr. Morris served in the USAF from 1982 to 1991 in space acquisition, launch operations, and HQ staff positions. He transferred to the USAF Reserve in 1991 and continues to be active with the rank of colonel. Mr. Morris's military honors include the Air Force Meritorious Service Medal, Air Force Commendation Medal, and Air Force Achievement Medal. He is a graduate of Air War College, Air Command and Staff College, and Squadron Officer's School, where he was a distinguished graduate.

GPS On and Off the Battlefield:
An Interview with Brig Gen John E. Hyten

In March 2008, Mr. Edward White of the Air Force Space Command (AFSPC) Public Affairs Office sat down with Brig Gen John E. Hyten, AFSPC director of requirements to receive an update on the Global Positioning System (GPS), both current and future. The following text is the result of that interview.

Interview

White: Does the Air Force consider and manage GPS as a satellite system or as separate satellites that provide positioning and timing service to its users, both military and civilian?

Hyten: You have to look at it as a system of systems. The ground elements, the link elements from ground to space, and the space systems all have to work together for GPS to deliver its service. GPS provides capability for positioning, navigation, and timing [PNT] around the world. The user segment, the ground system, the links, the ground stations around the world, partner with the National Geospatial Intelligence Agency, the satellites themselves, the operators—all are required to make GPS work.

So, it is a whole lot more than just the satellites. It is a whole lot more than any one piece of it. If any one of those pieces doesn't work, GPS doesn't work. If the ground segment at Schriever AFB [Colorado] doesn't work then the GPS constellation doesn't work for very long.

White: Putting this all together is quite a success story.

Hyten: GPS is one of the greatest success stories in the history of AFSPC and the history of the Air Force. It went through some tough times getting started. Challengers asked, "why is a satellite navigation system really needed? We have inertial navigation systems in airplanes, so why would you need a space-based satellite navigation system?"

I think there may be a few people like Dr. Brad Parkinson and a few others out there, but not many, who thought of all the uses for GPS in the future. However, until satellites got up there and people started working with them we didn't know how effective and useful the system could be.

And then the big decision to turn off selective availability by President Clinton was a huge step forward because that opened up GPS to the commercial market place. The decision last year to not even put selective availability on the future block of GPS satellites should increase confidence world-wide. GPS is going to continue to grow—and you see it everywhere, from bass boats to your car, to golf carts, to precision weapons.

White: It is an immensely important system of systems. What is the next step? Where are we going?

Hyten: We are going to continue to improve GPS. One of the great things about the Air Force and what AFSPC has done with GPS is that we don't just deliver the minimum capability. Right now, we have more operational satellites on orbit than we have ever had before, 31.

Last year, we completely replaced the ground system at Schriever; actually, we replaced two ground systems there. It used to take two squadrons to operate GPS, now it takes just one. That one squadron is operating the Launch and Anomaly Resolution Disposal Operations and a new ground system called the Architecture Evolution Program, but it is one squadron doing the whole business on a modernized system.

So, you put those modernized systems together with all the new satellites and there is no doubt that GPS has become the gold standard for precision navigation and timing in the world. Every year, the signal has gotten better. Every year, the accuracy of the system has gotten better. And that is what is going to continue. We are not only going to continue to improve the accuracy, we will continue to support the system and we are going to add capabilities in future blocks that will allow the system to be even more robust in a contested environment.

Lt Col Harold "Stormy" Martin, Air Force Space Command lead for Positioning, Navigation and Timing (PNT) (left) discusses PNT issues with Brig Gen John Hyten.

White: All the things that have come from the simple concept of a clock in space are incredible. I was reading that the timing signals the banking industry uses are based on GPS.

Hyten: The timing signal, from a civilian standpoint, is probably more important than the navigation signal because an accurate time stamp is needed for everything from traffic lights to banking. If you want to use your debit card in a gas station, that whole system is timed off of GPS. If for some reason GPS stopped working you would not be able to use your credit card in a gas station. You would not be able to go up to an ATM and get your money.

The whole financial system's timing system is based off of GPS. It is just amazing, because it is the most accurate clock and it is kind of omnipresent. People have figured out how to take advantage of it and it is a whole lot cheaper than building your own clock. All you have to do is pull the time off the satellites and use it.

White: And the government pays for it?

Hyten: The Congress actually passes the budget and the president signs it, but the United States Air Force is the steward of that system. Congress has been very kind in supporting that program and the president has supported that program for a long time. And because of all this support, GPS has become the gold standard for the world, no doubt about that.

White: What kind of feedback do you get from the users?

Hyten: It is pretty exciting. We had a tech sergeant who was in Afghanistan in a tough battle. He was in the fight for 24 hours, calling in air strikes. We were dropping 2,000 pound bombs within a few hundred yards of his position and he rarely saw an airplane. What he saw was bombs going off, taking out the enemy, helping him fight and win. A couple years ago, we brought him out to Schriever just so he could see how we operate GPS, and his classic line was, "I didn't know all this stuff was here and I really didn't care, I just knew that it worked." And that is really the bottom line.

I was talking to a farmer from Iowa who uses GPS to lay down all the seed, all the fertilizer. His combine uses GPS technology. He loads all the coordinates describing what he wants to do and where he wants to go—the various equipment, the tractor, the combine all work off of GPS—the equipment then knows how much to lay down, how much to pick up, and where to go depending on where they are. That is a great capability for farmers.

Everyone from a young Soldier, or a young Airman, in Iraq and Afghanistan, to a farmer in Iowa is dependent on GPS and we get awesome feedback from them all. When I was the wing commander at Schriever, it was pretty exciting to get that feedback. Even many people in Colorado Springs don't realize that everything that is GPS happens because of Schriever AFB. The folks in Los Angeles deliver the capabilities, but all the operations are based out at Schriever. We have ground stations around the world that we hook up to, but it is the folks at Schriever that hook into those ground stations that go up on the satellite. It is really an amazing national treasure.

White: Are there any urgent operational needs statements currently in the system regarding employment of GPS?

Hyten: The thing that is important to understand about GPS is that it is in the fight, real-time, every minute of every day and every day somebody is calling back to either the JSpOC [Joint Space Operations Center] at Vandenberg AFB [California], or sometimes, directly into the GPS operations center at Schriever, asking for specific help on a specific mission going on somewhere in the world.

Whether it is a GPS timing signal in a communications handset, a navigation signal in a handheld receiver, or whether it is a navigation signal built into an airplane, a tank, or a truck, everything is based on GPS. Every once in a while, when something is not working quite right in the field—it is nearly always working great in space—but we still need to work out the problem.

There has been a big transition in the last five years in how we provide GPS to warfighters in particular. It used to be that we just worried about the accuracy of the signal in space. We just tweaked everything we could to make sure that the signal was as accurate as possible. But that is not really the right measure of merit. The right measure of merit is how accurate that signal is to the user on the ground. Is he getting the signal? And if there is a problem you can't just say, "the signal in space is fine." You have to figure out for the Soldier, Airman, Marine, or Sailor, what the problem is and help them work through it.

We are really focused on delivering capabilities that allow warfighters to generate the combat effects they need, not just making sure that the signal in space is accurate. Every day we have urgent operational needs, mostly informal, that get worked in real-time to make sure the system is there for the warfighter.

White: The system has been referred to as an enabler, but isn't it more of an empowerment?

Hyten: I am not sure that either one of those terms is sufficient. I believe it is fundamental to the conduct of military operations today and it is fundamental, basically to our entire economic infrastructure.

If you say it enables, you're suggesting it makes things better. It does make things better, but if GPS just enables things and if it went away everything would be okay. We would just do things a little slower. If it went away, in many cases, we would be in a world of hurt. To me, GPS is fundamental to military operations and it is fundamental to our economic infrastructure.

White: Are there a couple of generations of GPS satellites?

Hyten: There are more than that. There are 13 Block IIAs, 12 Block IIRs, and five Block IIR-Ms. And there are the IIFs we are getting ready to launch next year. The fifth IIR-M launched in December of 2007. All five IIR-Ms have been successful; they are doing very well.

The IIR-M is a modernized IIR and has additional signals that will help additional users. It provides better accuracy in many ways. Altogether, there are three generations of satellites and there is about to be a fourth. Then, after that, there will be Block III.

And, depending on how long the IIA's end up lasting we could

have four or five generations of satellites all providing GPS capability. It is pretty amazing when you think about it because they are all operated on the one ground system at Schriever.

White: What is their expected lifespan?

Hyten: They are different. For the IIA's the design life is about seven and a half years and nearly all are way, way beyond that. The IIR design life is ten years and one of the IIR's is already beyond that. A lot of the satellites are well beyond their design life.

That comes from a couple of things. One is that the satellites themselves are proving to be more robust than we originally thought. They actually operate in medium Earth orbit, which is a very dirty environment in space. There is no such thing as a pure vacuum in space. There are all kinds of charged particles, solar particles, all kinds of things that we have to operate through in space. The medium Earth orbit is in many ways a dirtier environment than any of the others. So, one of the concerns was that we were going to have problems with our satellites when we put them up. But, because of good design by a number of different vendors, they are lasting longer.

The Boeing Delta 2 rocket launches from Cape Canaveral Air Force Station's pad 17A on 25 September 2007 carrying the GPS IIR-15 navigation satellite.

And then, there is the ability of our Airmen, supported by what we call "the back room folks." The back room folks consist of blue suit engineers supported by some very smart civil service employees and contractors. When a satellite does break, the back room folks have the amazing ability to go up on that satellite and figure out how to fix it through redundant components or other adjustments. They can bring that satellite back up, so it lasts even longer.

There is one satellite, one of the oldest. I believe that it lasted about 17 years on orbit, an old IIA. It was called Lazarus because they had actually gone through all the redundant components and there was nothing left, and they went back to a clock that had already died once, died, euphemistically. They said, "Let's turn that one back on and see if we can settle it out." There are four clocks on each satellite. So they turned the clock back on, got it to settle out, and it lived years longer. Pretty neat stuff!

White: Many say, space is a contested environment. Is there a backup? Say, there was a catastrophic failure. What would be the "plan B" for GPS?

Hyten: In the military we have a number of different methods for plan B. We still have inertial navigation systems on planes. We still have compasses. We still have watches. We still have the ability to operate like we did before GPS. All that capability is inherently there. But we wouldn't have the capability, if GPS went away, to use satellite navigation. So, we would have to use navigation and timing by some other means.

We have those other means and we can go back to them. We don't practice operating without GPS as much as we should but we could go back and do that. We operated without it for generations.

On the civil side, for navigation, there is a backup system called eLoran that provides a backup navigation and timing signal through a bunch of ground nodes, mostly along the coast. It was originally built to allow that kind of capability around ports.

There is a backup, but it is more of a navigation signal only. It doesn't do anything for the banking system, for the farmer in Iowa, for the ATM system, or the stoplights downtown. You can imagine the chaos that would ensue if all of those things stopped working.

This is one of the reasons why, if you go out to Schriever, you have layers of security before you can get to the nugget that is in the middle. We have very active security and in various places around the world we have redundant capabilities. We now have a backup capability that is in a geographically separate location. If Schriever went away completely, we could go to another location, bring everything up, and operate GPS just fine. We have a very robust capability to keep the GPS system going. We work very hard to make sure that nothing happens to GPS.

White: If we can go back to the Block III for a second. What increased capabilities does the Block III bring that are not available in earlier models?

Hyten: To me the most important thing GPS III brings is a larger bus, which is the platform of the satellite. It allows you to

do additional things. It has more power so it can provide more power to the ground. The GPS signal right now is very weak, GPS III will provide signals that would be hard to interfere with, either accidentally or on purpose. In the future we will have a more robust power system in space. We can then transmit a more powerful signal to the ground.

We will have a lot of anti-jam capabilities on those future satellites that will make the system more difficult to jam, more robust, more capable, and will allow us to fight through a lot of different problems that we really can't do with the previous versions. Our efforts are focused on the warfighter. Most of the new capabilities are designed to provide that ensured navigation and timing signal to warfighters around the world.

White: But, is it still available to the civil users?

Hyten: Absolutely. It has more robust civil signals, and it has a lot of different features that, through multiple signals, should be able to provide more accurate capabilities to civil users, assuming you build a new ground set.

Remember, GPS is much more than just the satellite—GPS user equipment can improve accuracy even further by taking multiple signals and correcting for errors created by the ionosphere.

White: It bounces it around a little bit?

Hyten: Yes, but say you have two signals coming through, you can actually see the error and through mathematical understanding you can take that error out and get a more accurate position. Most of the military signals work that way, but not all the civil signals do. They sometimes use just a single channel today.

Future capabilities will have more civil signals so it allows civil and commercial companies to build more accurate capabilities in their ground system, should they want them. A lot of them want to do that since they like to provide more accurate capabilities to their customers, it opens up a lot of things for the civil users. Most of the stuff we are putting on GPS III, besides the additional signals, provides a more robust capability to allow warfighters more assured access.

White: How many satellites are planned for the constellation? Is there an upper number?

Hyten: The requirement is 24 satellites plus three spares on orbit. Twenty seven is the requirement to provide enough accuracy. We are flying 31 satellites right now. Thirty is kind of the magic number. If you look at most of the analyses, the best performance is reached at 30 properly spaced satellites.

The key is spacing them correctly and having enough in view so you see enough satellites to get a very accurate signal. We don't want to drop below 27, because then we start having issues with certain points on the globe that will have slightly less accuracy from time to time. But if we can stay up to 27 and ideally at 30, the system will be very robust—and that really is a question of how long each satellite lasts.

There is a little bit of art in keeping the constellation populated, because you have to try to estimate when the satellites are actually going to die. It is a hard thing to figure out because they tend to last longer than their design life. You don't want to spend a lot of money to put more satellites on orbit when you have a healthy constellation already.

Then again, you know they are going to break because they all eventually die and you can't go back and refuel them and you can't go up and change out parts. You have to plan carefully to populate ahead of time. There is a lot of math, science, and statistics to figure it all out. We have done really well in the last half dozen years keeping the constellation populated. Right now, we have the most robust constellation in history.

White: Is GPS the only system that is free to the users?

Hyten: Well, it is the only one that is free to the world. Every system that is out there, GLONASS, and soon Galileo, they are all free to certain users. I am not sure of what the Russian business plan is for the commercial use of GLONASS. I don't spend a lot of time looking at the Galileo business plan for how they want to compete with GPS, but I know that they have a charge plan in mind to try to recoup certain costs.

It is a fairly complicated issue but we have made the decision

US Air Force SSgt Thomas Sylvester, of the 332nd Expeditionary Security Forces Squadron, marks the point of impact with a GPS locator after a simulated indirect fire attack during a training exercise at Balad AB, Iraq, 28 September 2007.

in the United States that GPS is a global utility that anybody can work off and we have decided that it is in the best interest of not only the United States, but the world to make GPS the gold standard for space-based navigation and timing and a utility available to the world.

I believe the decisions made by the leadership of this country in GPS have been tremendous. One of the reasons that GPS is the gold standard is because of the decisions the national leadership have made about turning off selective availability on the current constellation and removing the capability for selective availability from our future satellites. That just builds confidence in our international partners. They know GPS is going to be there when they need it.

White: How much of a role does civil need play in the development and modernization of the constellation?

Hyten: There are three partners in GPS, the military user, the civil user, and the commercial user. We have to consider all three partners in the decisions that we make on GPS. It is operated by the military, so, if I had to give a tiered approach, the first tier would be the military; second tier would be civil, FAA [Federal Aviation Administration], NOAA [National Oceanic and Atmospheric Administration], NASA; and the third tier would be commercial. It is a government system, built originally for the military, and we have people that are risking their lives every day who depend on it.

To me the military side has to be slightly higher than civil, but civil is critical because the infrastructure we have in this nation depends on it. You also have the commercial marketplace that is worth billions of dollars and is a key piece of the entire world economy, and you can't ignore that. You have to treat all three of them as partners in the system.

But, when it comes to priorities, there is a tiered order of precedence that is inherent in the process but we cannot ignore any one of those three areas. If we do, we are damaging the United States and either our economy, our infrastructure, or our military. You have to effectively integrate all three of them.

White: That is a huge responsibility.

Hyten: It is a national responsibility and an international responsibility. It is something that is difficult to work because most people that come to work GPS are military folks who have operated within military systems for a long time. Now, all of a sudden they are working on a system that is not only a military system, critical to the fight that we are in today, but it is also a national treasure that is involved in almost everything this nation does.

There are elements in the Coast Guard that work GPS from the civil perspective and there are elements on the commercial side that work various pieces of the GPS. We work with those folks all the time. It still comes back to Schriever and it still comes back to the Air Force for what we are going to do.

There is a national PNT Executive Committee that is co-chaired by the deputy secretary of defense and the deputy secretary of transportation. And now the deputy secretary of agriculture is going to be a member. The Department of Commerce is also a member. It is still chaired by defense and transportation, but really, all the elements of government are coming on board. Even though the Air Force is the one that has the budget for most of it, the national PNT Executive Committee is really the overarching piece of our federal government and has members from all elements of government. Commerce represents the commercial sector, transportation and agriculture represent the civil sector. NASA is there, NOAA is there, everybody has a voice at a senior leadership level to make sure that we do the right thing by GPS. And in many cases, it is that process that has allowed the key decisions which have enabled many GPS successes.

White: If you could look out five years, 10 years, 15 years, what is in the future for GPS?

Hyten: Better capabilities. I see us continuing to fly a constellation of about 30, and never less than 27. I see each one of those satellites being more capable, and I see our ground system and infrastructure being more robust and capable so the signals that go to the world 10 years from now will be even more accurate.

But the key piece that we always have to work at is "Never go back. Always keep moving forward." That is what we have done for over a decade; really, sincerely managed the GPS so that it has always moved forward. And I see us always moving forward.

We are not going to have a constellation of 40 satellites. The effective use of the taxpayer's dollars is to make sure that the constellation is about 30, always 27 and always as accurate and capable and robust as it can be, so that it operates in a number of different environments. That is where I see GPS going.

White: The one thing about space support is that it is so ubiquitous, and yet people don't realize that it is there. It is like the silent service, if I may borrow a term from the Navy. That seems like it is both a blessing and a curse. How would you respond to that?

Hyten: I look at GPS as a global utility. When you go to the wall and you flip the light switch on, nobody thinks any more about the power line, the grid, the power station downtown, the coal plant, the mining of the coal, the delivery of the oil, the dams that produce hydroelectricity, the nuclear power plants … nobody thinks about that. All they think about when they flip that switch is that the light comes on and that is what they expect. It is the same way with GPS. When they use their ATM card at the gas station they expect it to work. When they pull out their GPS receiver, they expect to know where they are. When they drop the bomb, they expect that bomb to go exactly where they told it to and it does.

So, it really is a global utility and I think that our responsibility really goes back to that tech sergeant I was talking about when he said, "I didn't really know where the stuff came from, I just cared that it worked." Our job is to make sure that the country and the world have confidence that GPS is going to work. And that is fine with me. I don't have a problem with that. I look at that as a strength of GPS. People trust it to work, and we make it work. That's what it is all about.

Members of the 310 Space Wing and 50th Space Wing completes transition to new GPS control system.

If you talk to anybody who is part of this new silent service they feel the same way. Because the key is that you always have to deliver and when the system works you have no problem explaining to the people who are utilizing it what difference it makes in their world.

White: One last question, could you tell us about the people who provide this service?

Hyten: To me, the best part about this system is that it is operated by some really great people, from commanders, Col Teresa Djuric at the 50th, Col Clinton Crosier at the Operations Group, into the squadron, into 2 SOPS [2nd Space Operations Squadron], and including the leadership all the way down. They are tremendous people who live and breathe the mission. We have a huge cadre of great engineers and acquisition professionals in Los Angeles who probably know GPS better than anybody in the world. They are a tremendous part of the team.

But for me, the most impressive thing, by far, is walking out on the ops floor and seeing the individuals who are already sending the commands to the satellite. He or she loads the navigation signal on the satellite and updates the timing. That person, invariably is a young Airman, who is about two years out of high school. A 19 or 20 year-old American, and they are the ones that are responsible at the business end.

Nobody else in the world tells the satellite what to do except those Airmen. To watch them do their job and to know how professional they are is the most amazing thing about GPS to me—we entrust the entire infrastructure of the country, our everyday warfighting operations to young Airmen who do the job and they do it spectacularly well—better than we ever have before. That is just a tremendous thing to watch and see.

Everybody is part of the GPS team, the engineers in the back room, the engineers in Los Angeles, the entire infrastructure, the folks in the headquarters that work all the administrative issues—but it all comes down to making sure that Airman, sending the commands to the satellites, has the tools and training he or she needs to make the satellites work.

White: Is there anything else you want to add to what we have already discussed?

Hyten: You can't say it often enough. GPS has become the gold standard for the world. Our job is to maintain that gold standard. And we are going to do it because it is critical to so many essential capabilities, both military and civilian.

One of the highlights of anybody in the space business is being able to walk into the 2nd Space Operations Squadron and understand that right here we are changing the world every day. It is pretty cool to be a part of that, whether here in the headquarters, out at Schriever or in Los Angeles, or wherever you happen to be—it is cool to be a part of it all.

White: I think you have one of those special jobs.

Hyten: Oh yeah, there is no doubt about it. I am the director of requirements now, but the real special job is Colonel Djuric's job at Schriever, and the 50th Operations Group job, and that Airman's job. They are actually doing it every day. To me, that is as good as it gets.

But as a staff guy here, I am now responsible for making sure that the next generation of GPS satellites produce the right capabilities. That is a pretty nice transition from the job I had at Schriever as the wing commander. It is a special job, there is no doubt about it. I am very fortunate to have this position.

Interviewed by Mr. Edward T. White, writer, Air Force Space Command Public Affairs Office.

Brig Gen John E. Hyten (BA, Engineering and Applied Sciences, Harvard University; MBA, Auburn University) is the director of Requirements, Headquarters Air Force Space Command (HQ AFSPC), Peterson AFB, Colorado. He is responsible for ensuring future space and missile systems meet the operational needs of our joint forces into the 21st century.

General Hyten was commissioned through the Air Force Reserve Officer Training Corps at Harvard University in 1981. His career includes assignments in a variety of space acquisition and operations positions. He has served in senior engineering positions on both Air Force and Army anti-satellite weapons system programs. His staff assignments include tours in the Air Force Secretariat, on the Air Staff, on the Joint Staff and as the director of the Commander's Action Group at HQ AFSPC. He served as a mission director in Cheyenne Mountain, and has commanded at the squadron, group and wing levels. In 2006, he deployed to Southwest Asia as director of space forces for Operations Enduring Freedom and Iraqi Freedom. Prior to assuming his current position, General Hyten commanded the 50th Space Wing at Schriever AFB, Colorado.

GPS Modernization and the Path Forward: **Bringing New Capabilities to** Military and Civil Users Worldwide

Dr. Donald G. DeGryse
Vice President, Navigation Systems
Lockheed Martin Space Systems Company
Newtown, Pennsylvania

A vital component of our nation's space infrastructure is the Global Positioning System (GPS), a network of satellites and associated ground components managed and operated by Air Force Space Command (AFSPC) at Schriever AFB, Colorado.

America and much of the world depend on GPS for accurate position, navigation, and timing (PNT) information and this space-based asset has become essential to the military as well as the public at large.

The US armed forces' ability to successfully execute global operations with great speed and effectiveness is significantly enhanced by the precision location, guidance and navigation capabilities delivered by GPS. Most recently, the system was integral to every military branch in the US-led coalition's success in Operation Enduring Freedom and Operation Iraqi Freedom.

For example, special forces mounted on horseback in Afghanistan summoned GPS-guided precision air strikes to engage enemy targets with pinpoint accuracy and then used the system to navigate safely back to base.

Likewise, in Iraq, GPS demonstrated its value by allowing Air Force pilots to streak through the sky with confidence because they knew exactly where they were and where they needed to go. It would be difficult to fight today's conflicts without this enabling technology.

In addition to providing mission critical capabilities to our men and women in uniform, the system also delivers essential services to civil users around the globe. We know that GPS is increasingly used in cars to help drivers navigate unfamiliar roads and highways, but we also use it in our daily lives and may not even realize it, for instance: (1) bank automatic teller machines rely on GPS to accurately record the time of monetary transactions; (2) international commerce in the stock market is calculated as GPS technology records the exact moment when stocks are traded to insure accurate exchange rates; (3) much of the food we eat is farmed using GPS; and (4) in addition to plowing and fertilizing, farmers use it to generate yield maps to identify fields where fertile soil produces the best crops.

Indeed, GPS serves us every minute of every day, no matter where we are on the planet. New applications continue to be created and like the Internet, the possibilities for satellite navigation are limited only by the human imagination.

As a result, the GPS industry continues to experience tremendous growth. ABI Research, a market research firm in Oyster Bay, New York, estimates last year's market for satellite navigation hardware was $33 billion, a $6 billion increase from 2006.

Figure 1. Artist's rendering of the Lockheed Martin Global Positioning Satellite IIR-M.

This growth was attributed to falling prices for all types of hardware and dramatic volume increases in the sales of portable navigation devices and satellite navigation equipped mobile phones in Europe and North America. The company forecasts the satellite navigation market growing to $54 billion worldwide by 2011.

The need for improved navigation is obvious and a space-based approach answers the need for accuracy, timeliness, and coverage as no terrestrial system can, which creates entirely new markets for GPS.

GPS Modernization

Since 1989, Lockheed Martin has worked with the GPS Wing, Space and Missile Systems Center, Los Angeles AFB, California, as prime contractor for the GPS Block IIR program. The company built 21 satellites to improve navigation accuracy and provide longer autonomous satellite operation than previous GPS spacecraft.

But as with all technological benefits, there is the responsibility to ensure its continued availability and preserve its competi-

tive and military advantages through continuous improvements. To bring new capabilities to the GPS constellation, the Air Force embarked on an effort to modernize eight existing GPS IIR spacecraft in storage. Known as the Block IIR-M series, these satellites include features that enhance operations and navigation signal performance for military and civilian GPS users around the globe.

Each satellite in the Block IIR-M series includes a modernized antenna panel that provides increased signal power to receivers on the ground, two new military signals for improved accuracy, enhanced encryption, and anti-jamming capabilities for the military, and a second civil signal that provides users with an open access signal on a different frequency.

Lockheed Martin and ITT have completed work on the eighth and final modernized spacecraft, which also includes a demonstration payload that will temporarily transmit the new third civil signal, known as L5. This spacecraft, known as SV 09, is one of the final three Block IIR-M satellites planned for launch in 2008.

Future generations of GPS spacecraft, including the Block IIF program that will launch next year, will include an operational third civil signal to further improve the accuracy and performance capabilities of the system.

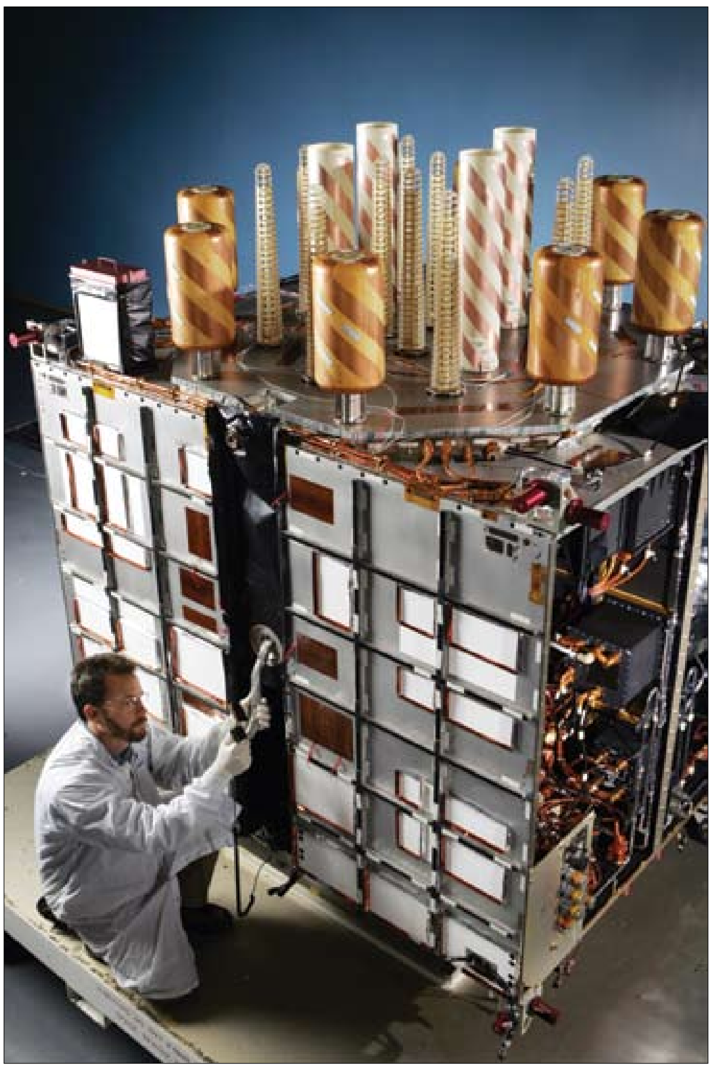


Figure 2. A technician at Lockheed Martin's facilities in Valley Forge, Pennsylvania, works on a modernized Global Positioning System Block IIR (GPS IIR-M) satellite.

Flight Operations

Upon successful launch of a IIR-M satellite, Lockheed Martin's operations team works closely with AFSPC's 2nd Space Operations Squadron (2 SOPS) and its reserve associate unit 19 SOPS based at Schriever AFB to quickly and efficiently conduct the on-orbit deployment and checkout of all spacecraft systems. After completion of navigation payload initialization, the satellites are then declared operational for both civil and military users.

The GPS IIR-M satellite launched on 20 December 2007, is an excellent example of the US Air Force/Lockheed Martin team's responsiveness in allowing these spacecraft to begin service as quickly and efficiently as possible. The joint team completed a record-setting on-orbit deployment in just over three days and then the satellite was declared operational on 2 January 2008 for both civil and military users.

Today, the Block IIR-M satellites, as well as the 12 original IIR satellites on-orbit are delighting users with significantly improved operations and navigation signal performance worldwide.

Based on the navigation user range error, which measures GPS accuracy, the Block IIR and IIR-M satellites enable properly equipped users to determine precise time and velocity, and worldwide latitude, longitude, and altitude to within one meter.

While these successes are a vast improvement over the past, the GPS architecture will need to continually improve to meet future needs.

The more we rely upon GPS for precision warfare the more likely a potential enemy will attempt to disrupt its utility. Hostile jamming of GPS receivers aboard our smart munitions, missiles, aircraft, ships, and hand-helds used by our ground forces, and so forth, could degrade the accuracy needed to effectively engage their targets.

This leads to major security, vulnerability, and availability concerns not only for the military, but also for the hundreds of millions of civilian users around the globe who depend upon GPS for service, for their income, and for their safety.

Going Forward

In planning for the future, the US Air Force has established a next-generation program that will provide increased capabilities incrementally to better meet current and future needs.

Known as GPS Block III, the new program will improve PNT services for the warfighter and civil users worldwide and provide advanced anti-jam capabilities yielding improved system security, accuracy and reliability.

The acquisition of this program is based on the "back-to-basics" principles, an approach focused on mission success in military space programs, and calls for incrementally adding new technologies as they mature, so acquisition cycle time, cost, and schedule risk are reduced.

The first "Block" of these new satellites, designated GPS

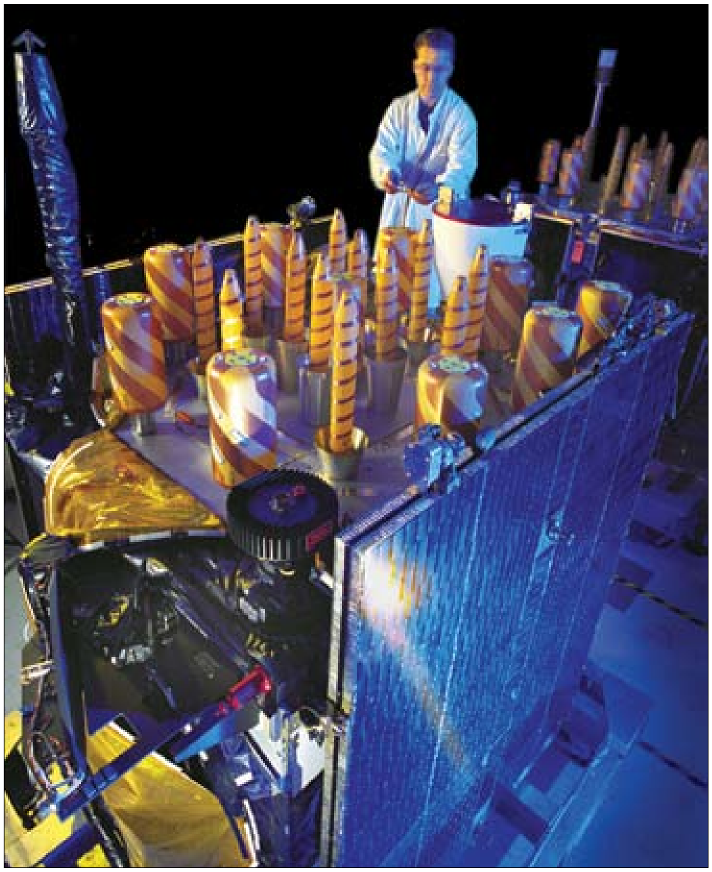


Figure 3. The GPS IIR-M series offers a variety of enhanced features for GPS users. Valley Forge, Pennsylvania.

IIIA, consists of eight GPS satellites with significant capability enhancements over the current constellation. For example, GPS IIIA provides greater than a fourfold increase in accuracy, reducing the likelihood of collateral damage and is more compatible with the use of low cost, smaller warhead, precision munitions like the small-diameter bomb.

In addition, GPS IIIA adds an order of magnitude improvement in jamming resistance making it extremely difficult for the enemy to disrupt or deny our effective use of the GPS signal. The initial launch of GPS IIIA is projected for 2014. Eight GPS IIIB and 16 GPS IIIC satellites are planned for later increments, with each increment including additional capabilities based on technical maturity.

Last year, the Honorable Dr. Ronald M. Sega, then under secretary of the Air Force; Dr. Donald Kerr, director of the National Reconnaissance Office; and General Kevin P. Chilton, former commander of AFSPC, appeared before members of Congress to discuss the current US space posture.

In his testimony before the House Armed Services Strategic Forces Subcommittee, Dr. Sega cited GPS III as a good example of how back to basics and the block approach works. "The GPS IIIA satellite will go beyond current capabilities of GPS II, and provide a growth path forward for future blocks of GPS IIIB and IIIC, in subsequent increments."[1] The importance of interagency integration and collaboration across the space arena was another key topic in Dr. Sega's testimony. "Our goal is to create partnerships within the space community, which we believe are essential to delivering requirements on cost and on schedule, ensuring appropriate funding stability."

Developing the next generation of GPS satellites is also a major focus area of Lockheed Martin. Working closely with the Air Force, our experienced GPS III team has defined a low-risk, evolutionary program plan based on a strong foundation of solid program execution and operational performance.

As envisioned, the fully deployed GPS III space segment constellation is expected to feature a cross-linked command and control architecture, allowing the entire GPS constellation to be updated simultaneously from a single ground station (GPS IIIB). Additionally a new spot beam capability for enhanced M-Code coverage and increased resistance to hostile jamming will be incorporated (GPS IIIC). These enhancements will contribute to improved accuracy and assured availability for military and civilian users worldwide.

We are extremely proud of our role in sustaining and improving GPS. The overall success of the Block IIR program and the new modernized Block IIR-M series is a profound testament to the close collaboration and partnership between the Lockheed Martin and Air Force team.

We understand the importance of this critical system and stand ready to once again partner with the Air Force to engineer even greater capabilities that will better serve our warfighters and civil users around the world.

Notes:

[1] Staff Sgt Monique Randolph, "Senior leaders testify about Air Force space program," AF News, 5 April 2007.

Dr. Donald G. DeGryse (BA, Augustana College; MS and PhD, Mathematics, Colorado State University, Colorado) serves as vice president, navigation systems and program manager of the GPS program for Lockheed Martin Space Systems Company.

He previously served as the company's vice president and program manager of the Space Radar program, vice president of Business Development and Advanced Programs, vice president of Flight Systems as well as vice president of Business Acquisition.

Dr. DeGryse joined Lockheed Martin (formerly Martin Marietta) in 1981 and has held progressively more responsible positions within the company including vice president of Defense Systems for Space Systems Company, and vice president of Lockheed Martin Special Programs, headquartered in Fairfax, Virginia, where he was the technical lead for a major classified proposal and was also responsible for the integration of several large classified programs across various Lockheed Martin companies.

He served as professor of mathematics at Bowling Green State University, Ohio and Gonzaga University, Washington prior to entering industry. He has completed several company- and government-sponsored programs including the Defense Systems Management College, executive management course in 1996 and the Harvard Business School executive management program in 1986. Dr. DeGryse is currently an executive mentor.

GPS Integral to SpaceX Falcon Launch Vehicles and Dragon Spacecraft

Mr. Eric L. Hultgren
Avionics Engineer
Navigation, Guidance, and Control Analyst
SpaceX
Hawthorne, California

Mr. Nicholas S. Blackwell
Avionics Engineer
Navigation, Guidance, and Control Analyst
SpaceX
Hawthorne, California

From the moment of liftoff to the time recovery vessels close in, Global Positioning Systems (GPS) is employed by SpaceX's Falcon launch vehicles and Dragon spacecraft to significantly increase the reliability and reduce the cost of manned and unmanned space transportation. During ascent and orbital navigation, GPS provides vital position data. By using GPS in conjunction with a cost-effective inertial sensing system during on-orbit operations, SpaceX achieves the same accuracy expensive inertial sensing systems provide—but at a fraction of the cost. And when Dragon rendezvous and berths with the International Space Station (ISS) for NASA's Commercial Orbital Transportation Services program, GPS will assist the initial phases and provide a triply redundant system, satisfying stringent safety requirements for the common crew and cargo capsule. Finally, SpaceX's tracking and recovery team will employ combined GPS/Iridium systems for locating and retrieving returned booster stages, optimizing the efficiency and cost-effectiveness of recovery operations.

About SpaceX

Founded in 2002 by Elon Musk, Internet entrepreneur and co-creator of PayPal, SpaceX has already developed two new liquid-fueled rocket engines, a bipropellant thruster system, avionics, software, state-of-the-art structure, and propulsion test facilities. Additionally, SpaceX has established launch sites at Vandenberg AFB, California, and the Reagan Test Site at the Kwajalein Atoll in the Marshall Islands. A third launch site is under development at SLC-40, Cape Canaveral AFS, Florida.

To date, SpaceX has conducted two launches of the Falcon 1 rocket. The Falcon 1 launch vehicle family can deliver small payloads up to 2,200 pounds (1,000 kg) to low-Earth orbit (LEO). The next Falcon 1 launch is scheduled for June 2008, and will carry the Jumpstart mission for the DoD's Operationally Responsive Space (ORS) Office demonstrating the rapid integration and launch of space assets.

In addition, SpaceX is rapidly producing development and flight hardware for the far larger Falcon 9 rocket, which can loft up to 24,890 pounds (11,290 kilograms) to LEO. SpaceX typically reserves 10 percent of the mass-to-orbit performance (represented in these numbers), but this is negotiable. Falcon 9 will lift the Dragon cargo and crew carrying spacecraft, which can deliver over 5,500 pounds (2,500 kilograms) of cargo, or a crew of seven, to the ISS, and return the same to Earth.

GPS During Ascent and Orbit

GPS and inertial navigation systems combine on Falcon 1 to provide an accurate and cost-effective navigation solution. The use of the Iridium satellite telecommunications network for data transmission to ground provides a low-cost communication solution having nearly worldwide coverage.

During launch, Falcon 1 is guided to a pre-determined or-

Figure 1. Falcon 1 Demonstration Flight 2 reached an altitude of 180 miles (289 kilometers) on 21 March 2007, from Kwajalein Atoll in the central Pacific. The next Falcon 1 launch is scheduled for June 2008, and will carry the Jumpstart mission for the DoD's Operationally Responsive Space (ORS) Office.

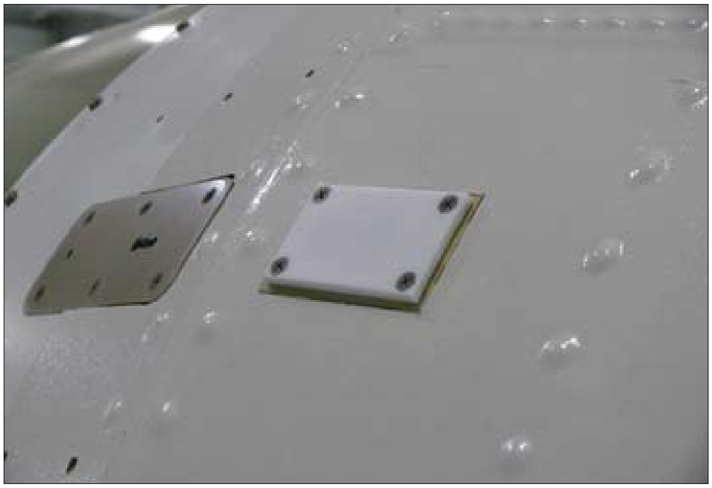


Figure 2. Falcon 1 uses two small patch antennas on opposite sides of the second stage to obtain a full view of the sky regardless of the rocket's altitude.

bit by a GPS receiver which provides navigation signals to the flight computer. The custom-ordered 14-channel receiver, in combination with an inertial measurement unit (IMU), provides a level of accuracy in vehicle position and velocity on par with that of much more expensive inertial-only navigation systems. Since the vehicle will greatly exceed the Coordinating Committee on Export Controls limits placed on commercially produced GPS units for altitude (11 miles/18 kilometers) and velocity (1,690 feet per second/515 meters per second), the GPS receivers must be customized with these restrictions removed in order to provide data throughout ascent.

When the first stage separates from the vehicle at an altitude of 50 miles (80 kilometers) and returns under parachute for an ocean recovery, three independent GPS receivers on the stage send their position data to the recovery vessel via the Iridium satellite network. The recovery vessel then picks up the stage for refurbishing and, ultimately, reuse. Meanwhile, after half an orbit, the Falcon 1 second stage performs an engine firing to circularize its orbit and then deploys the payload. Its GPS-derived position and velocity information is transmitted to the ground via the commercial Iridium satellite telephone system at the time of deployment.

GPS data supplement data from a fiber optic based, cost-effective IMU with moderate drift rate. The IMU provides high-rate data between GPS data points, while the GPS updates the navigation solution to correct for IMU drift. Importantly, before each GPS message is used, the flight computer verifies: that each message checksum is correct; that the position dilution of precision is nonzero and below a predetermined threshold; that the calculated position and velocity have changed since the last measurement; and that the calculated vehicle speed and altitude are within a physically reasonable range. These checks help ensure the accuracy of all GPS data used for navigation.

Combining GPS and Iridium Systems

The upcoming third flight of Falcon 1, scheduled for June 2008, will carry an experimental on-orbit navigation and telemetry system that offers the potential to greatly lower the cost of mission operations. This experiment seeks to demonstrate that an orbiting vehicle can connect to the Iridium network using the short burst data (SBD) protocol. Mission operators will receive the GPS-derived state of the Falcon 1 second stage in the form of low cost 'text messages from space.' The experiment's hardware will accept data from the GPS receiver and then transmit that information to the Iridium satellite network, which will deliver the messages as conventional Iridium data packets to the system's ground stations. This technology offers the potential of greatly lowering the cost of mission operations for telemetry reception outside the range of the main ground station, and will allow for the upward transmission of non-critical commands from the ground to the orbiting spacecraft.

The system uses a high performance GPS chipset, and provides a novel, low-cost solution for over-the-horizon telemetry and orbit determination. The experiment will operate in parallel with the rocket's flight-proven primary system, and will not actually control the flight. The self-contained system carries a high-performance GPS receiver, a commercial tracking modem for communicating with the Iridium satellite telephone network, a micro-controller, battery pack, and a dual GPS/Iridium patch antenna mounted to the structure of the Falcon 1 second stage.

Figure 3. Dragon spacecraft engineering model at SpaceX's new 500,000-plus square foot headquarters in Hawthorne, California.

Figure 4. Computer simulation of Dragon spacecraft approaching the International Space Station.

GPS for Navigation on the Dragon Spacecraft

All safety-critical systems carry stringent redundancy requirements. GPS receivers provide a triply redundant system for navigation during approach to the ISS. These, and all key elements of the system, including the pressure structure, avionics, propulsion, re-entry and landing systems, can be validated repeatedly in actual flight conditions prior to carrying crew. SpaceX currently has three Dragon cargo missions on the US launch manifest, including one flight in a demonstration-only configuration, and two flights of a rendezvous-capable configuration that will ultimately berth at the ISS.

The final Dragon configuration for berthing at the ISS will employ a primary high performance IMU, three secondary medium performance IMUs, and three GPS receivers that provide a triply redundant system for relative GPS (RGPS) navigation as Dragon approaches the ISS. As with Falcon launch vehicles, GPS receivers will be used to enhance Dragon's navigation solution, particularly in compensating for drift of the primary inertial navigation system. During the duration of a few orbits, an IMU-only solution would become inaccurate by a few kilometers. Adding GPS to the solution (whether filtered or unfiltered) compensates for this drift.

During rendezvous with the ISS, RGPS will be the primary method of computing Dragon's position relative to the ISS inside the approach ellipsoid (2.5 mi x 1.25 mi x 1.25 mi), and outside the keep-out sphere (radius 656 feet). It is anticipated that one receiver will be used for RGPS at a time, selected based on the number of satellites "in lock" that are common with the GPS receivers aboard the ISS. In a situation where the GPS devices receive insufficient signals or cannot otherwise be employed, an IMU-only navigation solution can be used to guide Dragon away from the ISS in a safe and controlled manner.

GPS for Recovery

Both Falcon 1 and Falcon 9 first stages are designed for recovery and reuse, and tracking and recovery teams will employ a combined GPS/Iridium system to locate the expended stages. Joining the abilities of the GPS and Iridium systems permits space assets to report their precise locations from essentially anywhere on or above the Earth. In addition, they are freed from the expense and range limitations inherent to ground station coverage. This system also provides significant advantages for Dragon recovery over the Apollo command module recovery beacons. By outfitting recovery vessels with the tracking systems, their relative location to the assets can easily be obtained, allowing a single operator to monitor and coordinate all recovery related assets.

Falcon 1's first stage carries three independent trackers, each with its own dual patch antenna. The trackers are activated before launch and managed by a remote operator who sets the report frequency and the state of the Iridium radio frequency (RF) board by sending an email to each tracker. The GPS board begins providing location data just prior to parachute deployment, once velocity and altitude fall below Coordinating Committee on Export Controls limits.

Recovery antennas are mounted on the exterior of the interstage assembly at several stations around the vehicle's circumference. The arrangement permits a view of the horizon for all

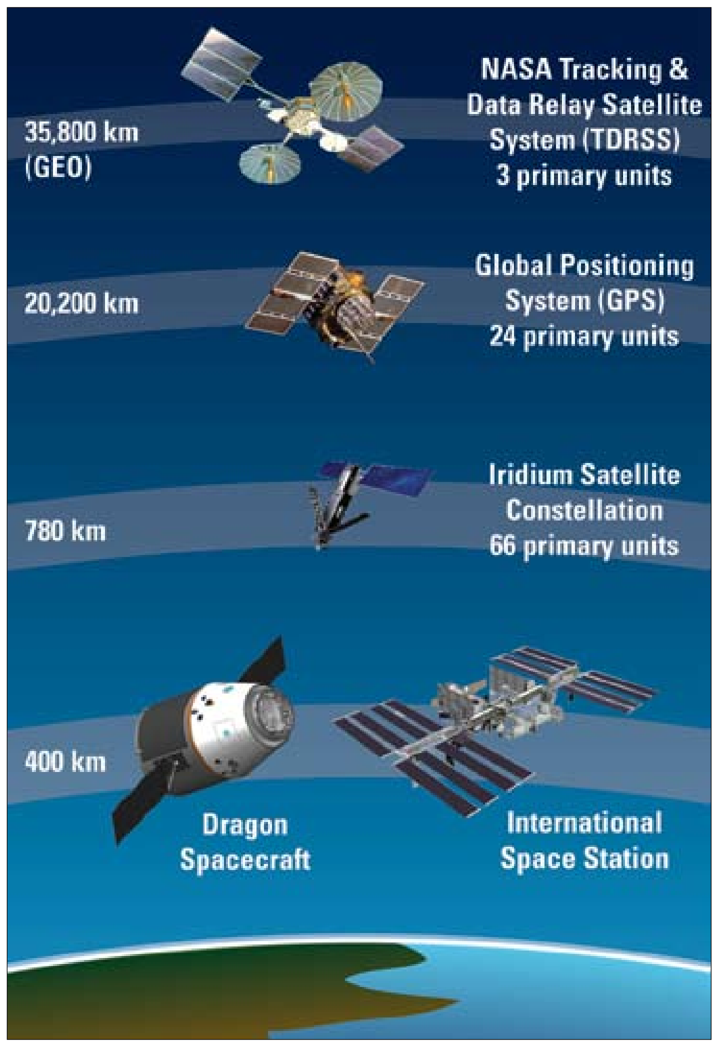


Figure 5. Satellite systems to be employed by SpaceX's Dragon spacecraft, as part of the NASA Commercial Orbital Transportation Services demonstration program.

Figure 6. Falcon 1 recovery pontoon in front of the Falcon 1 first stage test unit. Upon locating the returned first stage, the recovery vessel will inflate and deploy the pontoon, strapping it around the stage and towing it back to port for refurbishment and reflight.

three antennas during descent under parachute, and at least one antenna will have a full view of the sky as the stage rests on its side in the water. Each tracker is contained in a vibration isolated submersible enclosure with a 60-plus hour rechargeable battery pack, giving the recovery vessel, situated approximately nine kilometers from the nominal splashdown location, plenty of time to reach the stage before the trackers expire. Because the trackers are remotely configurable, the interval of GPS reports sent by the trackers and the state of the RF board can be managed to extend mission life, if necessary.

Although recovery of Falcon first stages will not carry the urgency attendant with locating and engaging crew-carrying vehicles, future Dragon spacecraft flights will. The GPS/Iridium tracking system has major advantages over the line-of-sight limited Apollo command module recovery beacons which required the deployment of multiple aircraft in the landing area to ensure the capsule could be located promptly after splashdown. Dragon will have ablative-coated, conformal GPS antennas for each onboard tracker. By utilizing the same system in both cargo and crew carrying missions, a single system will be flight qualified, which significantly reduces development costs.

All recovery vessels will be outfitted with the GPS/Iridium tracking systems, and thus be easily located relative to the assets to be recovered. Thus, a single operator will be able to locate and monitor all recovery related assets and coordinate recovery operations and personnel with maximum efficiency. Even under adverse circumstances where recoverable assets return outside targeted zones, and may be subject to ocean currents, the reliable and persistent GPS-derived, Iridium-reported position information should enable prompt location and recovery.

Conclusion

GPS plays an important role in all navigation and recovery systems developed by SpaceX, and contribute to the goals of increasing the reliability and lowering the cost of space transportation. It helps provide accurate data during ascent, orbital navigation, and during the initial phase of rendezvous and docking with the ISS. On orbit, employing GPS enables the use of lower-cost inertial sensing systems. The upcoming launch of a novel hardware system combining GPS and Iridium satellite networks for on-orbit communications seeks to extend the abilities of both of those systems, and to provide a new, cost effective method of two-way ground-to-orbit communications. Finally, using combined GPS and Iridium systems aboard recovery vessels, as well as the hardware targeted for recovery, provides for more efficient and cost effective ground operations.

Find more information on SpaceX launch services at: www.SpaceX.com.

Mr. Eric L. Hultgren (BS, Mechanical Engineering, Stanford University; MS, Aeronautics & Astronautics, Stanford University) is an avionics engineer and navigation, guidance and control analyst at SpaceX. Mr. Hultgren is the responsible engineer for recovery avionics on Falcon 1, Falcon 9, and Dragon, with additional duties related to reentry systems, navigation hardware, and guidance and control algorithms for the Dragon spacecraft. Previously, Mr. Hultgren was employed as a guidance and control analyst for advanced reentry systems at Lockheed Martin Space Systems Company.

Nicholas S. Blackwell (BS, Aerospace Engineering Sciences, University of Colorado at Boulder; MS, Aeronautics and Astronautics, Stanford University) is an avionics engineer and navigation, guidance and control analyst at SpaceX. He is responsible for several aspects of the Falcon 1 and Falcon 9 guidance, navigation, and control systems, trajectory design and analysis, and vehicle performance analysis.

Mr. Blackwell participated in the Citizen Explorer 1 small satellite project at the Colorado Space Grant Consortium while attending the University of Colorado at Boulder. Following his graduation in 2002, he became a satellite operations engineer for General Dynamics at the Naval Satellite Operations Center at Point Mugu, California. In 2004, he began graduate studies at Stanford University, where he focused on dynamics and controls. His interest in commercialization of space led him to SpaceX after earning his master's degree in 2005.

The International Committee on Global Navigation Satellite Systems:
Building a System of Systems for a Global World

Ms. Sharafat Gadimova, Programme Officer
United Nations Office for Outer Space Affairs
Vienna, Austria

Mr. Hans J. Haubold, Programme Officer
United Nations Office for Outer Space Affairs
Vienna, Austria

Global Navigation Satellite Systems (GNSS) consist of satellites, ground stations, and user equipment and are utilized worldwide across many areas of society. GNSS, operating in different constellations, include the United States' Global Positioning System (GPS), the Russian Federation's Global Navigation Satellite System (GLONASS), Europe's European Satellite Navigation Systems (Galileo), and China's COMPASS. Regional Navigation Satellite Systems (RNSS), providing signal coverage over a number of nations or regions, are India's GPS Aided Geo Augmented Navigation (GAGAN) and Japan's Quasi-Zenith Satellite System (QZSS). In an attempt to build a true system of GNSS systems in the coming decade, the International Committee on GNSS (ICG) was established in 2005 under the umbrella of the United Nations. The ultimate goal of ICG is to achieve compatibility and interoperability of GNSS systems thereby saving costs through international cooperation and making positioning, navigation, and timing available globally for societal benefits, including monitoring all aspects of environment and security.[1]

Establishment of the ICG

Following the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space, held in 1999, the United Nations General Assembly endorsed "The Space Millennium: Vienna Declaration on Space and Human Development." The Vienna Declaration called for action to improve the efficiency and security of transport, search and rescue, geodesy and other activities by promoting the enhancement of, universal access to and compatibility among, space-based navigation and positioning systems. In response to that call, in 2001, the United Nations Committee on the Peaceful Uses of Outer Space established the Action Team on GNSS to carry out those actions under the chairmanship of the United States of America and Italy.

The Action Team on GNSS consisted of 38 member States and 15 inter-governmental and non-governmental organizations and recommended that an ICG be established to promote the use of GNSS infrastructure on a global basis and to facilitate exchange of information.

Following workshops for the regions of Africa, Asia and the Pacific, Western Asia, Latin America and the Caribbean, Europe, international preparatory meetings and actions at the inter-governmental level, the ICG was established in December 2005. The ICG is an informal, voluntary forum where governments and interested non-government entities can discuss all matters regarding GNSS on a worldwide basis. The ICG promotes international cooperation on issues of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services.

The goal of the ICG is to promote the greater use of GNSS capabilities to support sustainable development and to promote new partnerships among committee members and institutions, particularly taking into account interests of developing nations.

Progress to Date

The ICG held its first meeting in Vienna in November 2006. At that meeting, the ICG adopted its terms of reference and work plan. Under its work plan, the ICG will consider the establishment of ICG information centers by GNSS providers for the GNSS user community. In addition, the United Nations Office for Outer Space Affairs (UNOOSA), currently serving as the executive secretariat of the ICG, developed a comprehensive information portal for the ICG and users of GNSS services.

Government members of the ICG currently include China, India, Italy, Japan, Malaysia, Nigeria, Russian Federation, United Arab Emirates, and the United States of America, as well as the European Community.

Associate members drawn from international organizations, representing users or specific application areas, include the Civil GPS Service Interface Committee, the International Association of Geodesy, the International Cartographic Association, the International Association of Geodesy Reference Frame Sub-Commission for Europe, the International GNSS Service (IGS, formerly International GPS Service), the International Society for Photogrammetry and Remote Sensing, the International Earth Rotation and Reference Systems Service, the Fédération internationale des géomètres, the European Position Determination System, the International Council for Science, and UNOOSA.

Additional observing organizations include the Committee on Space Research (COSPAR), the Bureau international des poids et measures, the International Association of Institutes of Navigation, the Union radio-scientifique internationale, and the International Telecommunication Union.

The second meeting of the ICG was held in Bangalore, India, from 4 to 7 September 2007, to further review and discuss global navigation satellite systems and their applications within the framework of the ICG work plan. These applications include security and economic development, particularly the efficiency and safety of transport, search and rescue, geodesy, land management and sustainable development, and other activities. The committee addressed the use of such applications to promote the enhancement of universal access to and compatibility and interoperability of, global and regional navigation satellite systems and the integration of these services into national infrastructure, particularly in developing nations.

A major development of the second meeting of the ICG was the establishment of the forum of GNSS system and service providers (Providers Forum [PF]) to enhance compatibility and interoperability among current and future global and regional space-based systems by exchanging detailed information about planned or operating systems and the policies and procedures that govern their service provision. The PF is not a policy-making body but will provide a means of promoting discussion among system providers on key technical issues and operational concepts such as protection of the GNSS spectrum and orbital debris/orbit deconfliction.

Information exchanged at the PF revealed that all current and future providers were committed to their plans to deploy and/or modernize their respective global and regional satellite navigation systems concerning the following important characteristics: (a) service to users was provided or would be provided from all systems in radio frequency spectrum bands internationally allocated for radio-navigation satellite services in L-band (960-1300 MHz and 1559-1610 MHz). Two systems would also broadcast a navigation signal in S-band (2491.005 ± 8.25 MHz). The band 5000-5030 MHz could be used in the future by one or more systems; (b) all systems were broadcasting or would broadcast an open service using one or more signals provided to users free of direct user charges; and (c) many systems also broadcast authorized services specifically designed to meet the needs of authorized users in support of governmental functions.

The third meeting of the ICG will be held in the United States in 2008. Preparations are already on-going for the fourth meeting of the ICG, to be hosted by the Russian Federation in 2009.

Executive Secretariat of ICG at UNOOSA

Pursuant to elements of the ICG work plan, the coordination of future programme plans among current and future GNSS operators, including augmentation systems, and increased awareness of the community of users will enhance the utility of GNSS services and should result in a number of new international and national programmes that support a broad range of interdisciplinary and international activities. These activities will need a strong outreach campaign on the benefits of the use of GNSS, particularly in developing nations.

If supported by GNSS system providers and users, UNOOSA, as the executive secretariat of the ICG and the PF, could develop a wide range of activities on GNSS applications, and encourage cooperation with and communication among regional GNSS reference systems.

Specifically in 2008, UNOOSA scheduled, as supported (in-kind and in-cash) by the US through ICG and in coordination with co-organizers, activities focusing on building capacity in using global navigation satellite systems to support sustainable development, as follows:

1. The services of global navigation satellite systems are currently being used in a wide range of sectors including but not limited to: mapping and surveying, monitoring of environment, agriculture and natural resources management, disaster warning and emergency response, aviation, maritime and land transportation. Taking advantage of the work carried out by UNOOSA in the framework of the Programme on Space Applications and supported by ICG, a workshop on the applications of GNSS will be organized jointly with the Satellite Navigation Group of the Colombian Commission on Space and the United States of America from 23 to 27 June 2008. The workshop will be held in Medellin, Colombia. It will examine the progress of the projects launched in a similar workshop in 2005, provide fresh impetus to projects that have not yet moved forward, and will also make way for new projects related to the implementation and use of satellite navigation technology.[2]
2. In view of critical new observations concerning the Earth's atmosphere and global climate, notably from the COSMIC, DEMETER, CHAMP, TIMED, ROCSAT, and DMSP satellites, GPS ground-based receivers, airglow instruments, and radars, all of which help provide clues to the complex plasma variations and electrodynamics of the F-region ionosphere during storms, UNOOSA and ICG will organize the session on ionospheric storms and space weather effects to be held on 23 May 2008 during

the week of the 12th International Symposium on equatorial aeronomy, Crete, Greece from 18 to 24 May 2008. This session will address all aspects of the response of the mid- and low-latitude ionosphere to magnetic storms and their space weather effects, including in-situ and ground-based observations as well as modelling and theoretical studies, particularly using GPS.[3]

3. Capacity-building efforts in space science and technology are a major focus of the activities of UNOOSA and of specific interest to ICG. Such efforts include providing support to the regional centres for space science and technology education, affiliated with the United Nations, whose goal is to develop, through in-depth education, an indigenous capability for research and applications in the core disciplines of: (a) remote sensing and geographical information systems; (b) satellite communications; (c) satellite meteorology and global climate; and (d) space and atmospheric sciences. The regional centres are located in Morocco and Nigeria for Africa, in Brazil and Mexico for Latin America and the Caribbean, and in India for Asia and the Pacific. Within the framework of the work plan of ICG, UNOOSA will develop the GNSS education curriculum for teaching GNSS applications as part of the four above core disciplines. Currently, the regional centres and ICG are exploring the possibility to have the regional centres also acting as ICG information centres. The ICG information centres would aim to foster a more structured approach to information exchange on GNSS applications in order to fulfil the reciprocal expectations of a network between ICG and regional centres. An international training course on satellite navigation and location based services will be held at the UN-affiliated Regional Centre for Space Science and Technology Education in Asia and the Pacific, in Ahmadabad, India from 18 June to 18 July 2008.[4]
4. In order to increase knowledge and expertise relating to GNSS world wide, UNOOSA as executive secretariat of ICG will organize the first ICG expert meeting on GNSS systems and services on 15 July 2008 during the 37th COSPAR Scientific Assembly, Montreal, Canada, from 13 to 20 July 2008. In this meeting, ICG will introduce the scope of its current and future work, aiming at building a system of systems. Its focus will be on identifying future needs and requirements, in terms of technology and applications, both at regional and international levels, and building on the experience of nations or regions around the world. The ICG work plan will be used as a guideline throughout the different sessions. Emphasis will also be placed on the further development of the strength of the ICG as a participant in the global playing field for GNSS activities.[5]

Notes:

[1] *Supporting Information:* The details on the ICG are available at the ICG Information Portal, http://www.unoosa.org/oosa/en/SAP/gnss/icg.html; Report of the Action Team on GNSS: Follow-up to the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III), United Nations, New York 2004; Report on the UN/USA International Meeting on the Use and Applications of GNSS, Vienna, Austria, 13-17 December 2004, UN document A/AC.105/846; First Meeting of the ICG, Vienna, Austria, 1-2 November 2006, UN document A/AC.105/879; Space Policy 23(2007)245-247; Second Meeting of the ICG, Bangalore, India, 6-7 September 2007, UN document A/AC.105/901; Space Policy 24(2008)58, 53-55.

[2] Information on United Nations/Colombia/United States of America workshop on the applications of global navigation satellite systems, to be held in Medellin from 23-27 June 2008, http://www.unoosa.org/oosa/SAP/gnss/index.html.

[3] Information on the 12th International Symposium on Equatorial Aeronomy, 18-24 May 2008, Crete, Greece, http://isea12.physics.uoc.gr/.

[4] Information on the international training course on satellite navigation and location based services, to be held at the UN-affiliated Regional Centre for Space Science and Technology Education in Asia and the Pacific, in Ahmadabad, India from 18 June-18 July 2008, http://www.cssteap.org/.

[5] The 37th COSPAR Scientific Assembly which will take place in Montréal from 13-20 July 2008 at the Palais des Congrès de Montréal, www.cospar2008.org/welcome_e.shtml.

Ms. Sharafat Gadimova (BS, Technology, Azerbaijan State Oil Academy, Baku, Azerbaijan; MS, Engineering, Asian Institute of Technology, Bangkok, Thailand) is a programme officer at the United Nations Office for Outer Space Affairs in Vienna, Austria. She is involved in the organization of the United Nations activities related to Global Navigation Satellite Systems (GNSS), particularly the development of the International Committee on GNSS and the activities of the United Nations affiliated regional centres for space science and technology education.

Previously, she worked for the Azerbaijan National Aerospace Agency in Baku and the Shirshov Institute of Oceanology, Moscow, the Russian Federation, as a researcher.

Mr. Hans J. Haubold (BS, Solid State Physics, Technical Chemnitz University, Germany; PhD and DSc, Institute for Astrophysics, Potsdam, Germany) is an astrophysicist from the Institute for Astrophysics, Potsdam, Germany where he has been professor of Theoretical Astrophysics since 1988. Since 1988 he has also been with the United Nations Office for Outer Space Affairs, firstly in New York and later in Vienna, Austria, since 1993. His principal responsibility is with the establishment of the UN-affiliated Regional Centres for Space Science and Technology Education in Africa, Asia and the Pacific, and Latin America and the Caribbean. At the United Nations he spearheaded the development of education curricula in remote sensing and GIS, satellite meteorology and global climate, satellite communications, and space and atmospheric science. Since 1991 he is the principal organizer of the series of annual UN/ESA/NASA workshops on Basic Space Science and The International HeliophysicaL Year. He supports Ms. Sharafat Gadimova in the operation of the ICG Executive Secretariat.

Promoting International Civil GNSS Cooperation Through Diplomacy

Ms. Alice A. Wong
Senior Advisor for GPS Issues
Office of Space and Advanced Technology
Bureau of Oceans, Environment and Science (OES)
US Department of State, Washington, DC

Mr. Ray E. Clore
Senior Advisor for GPS-Galileo Issues
Office of Space and Advanced Technology
Bureau of Oceans, Environment and Science (OES)
US Department of State, Washington, DC

The Office of Space and Advanced Technology of the US State Department pursues an active program of promoting international cooperation among present and planned civil Global Navigation Satellite Systems (GNSS) with the US Global Positioning System (GPS) as the central pillar in an emerging international system of GNSS. This article will provide an overview of US space-based positioning, navigation, and timing (PNT) policy, and give a summary of US diplomatic efforts on a bilateral, multilateral, and regional basis to support compatibility and interoperability among current and future space-based PNT providers.

US Space-Based PNT Policy

Like the Internet, the US GPS is now a critical component of the global information infrastructure. New applications for GPS are constantly being introduced, facilitating greater business efficiency, transportation safety, environmental protection, public security, scientific discovery, and so forth. Since its initial deployment, GPS has grown into a global utility, providing space-based PNT solutions in a stable and reliable fashion. Increasing adoption of GPS by businesses and governments for infrastructure use is made possible by the predictable and dependable US policy framework that allows open access to the necessary elements to develop new products and services based on GPS. This framework has strengthened over time, with several key milestones worth mentioning:

- In 1978 the first GPS satellite was launched.
- In 1983 President Ronald W. Reagan offered free civilian access to GPS to help ensure aviation safety around the world.
- GPS reached full operational capability in 1995.
- The first US GPS policy was signed by President Bill Clinton in 1996. It set in motion the decision to set selective availability (the ability to intentionally degrade the accuracy of civil signals) to zero in 2000, and included important principles such as the provision of the GPS standard positioning service for peaceful civil, commercial and scientific use on a continuous, worldwide basis, free of direct user fees. In 1997, the US Congress passed this principle into law and it remains in effect today.
- In 2004 President George W. Bush issued an updated US policy on space-based PNT that further improved the policy and management framework governing GPS and its augmentations to support their continued ability to meet increasing and varied domestic and global requirements.
- In 2007, at the International Civil Aviation Organization assembly, US Transportation Secretary Mary E. Peters announced that all new GPS III satellites will be built without the selective availability feature.

In addition to reaffirming open access to all information needed to design and build new products and services using GPS, a policy that has helped unleash the power of free markets and private enterprise for the good of all users worldwide, the 2004 space-based PNT policy defines key goals that include: providing uninterrupted availability of space-based PNT services; remaining the pre-eminent military space-based PNT service for US and allied use; continuing to provide civil services that exceed or are competitive with other civil space-based PNT

5th US-Japan GPS Plenary Meeting held in May 2007 in Washington DC.

services; remaining an essential component of internationally accepted PNT services; and promoting US leadership in space-based PNT applications.

To accomplish these goals, US diplomatic efforts encourage foreign development of PNT services and systems based on GPS; and seek compatibility and interoperability between foreign space-based PNT systems and GPS and its augmentations. Compatibility in this context means the ability of two or more space-based PNT systems to be used separately or together without interfering with each individual service or signal. Interoperability refers to the ability of multiple civil global or regional space-based PNT systems to be used together to provide better capabilities at the user level than would be achieved by relying solely on one service or signal.

Space-Based PNT Diplomacy

Although the importance of space-based PNT compatibility and interoperability has come into sharper focus in the years immediately preceding and following the 2004 policy release, international discussions on satellite navigation have been underway for more than a decade. In the early 1990s, our office established the GPS International Working Group (GIWG) to facilitate coordination among the US agencies working on international GPS policy issues and cooperation approaches. GIWG members include all relevant departments of the executive branch, including defense and transportation, and their reporting organizations responsible for key aspects of GPS and augmentation service provision, such as the Air Force and the Federal Aviation Administration. Although the spectrum of bilateral and multi-lateral diplomatic activities discussed below are led by the US State Department, our successes to date would not be possible without the technical expertise, programmatic prowess, and years of experience provided to these on-going consultations and negotiations by subject matter experts from other federal departments and agencies.

Bilateral Cooperation

The US has many productive bilateral relationships on satellite navigation issues. US-Japanese cooperation on GPS has included regular policy and technical consultations since 1996 and is currently based on the 1998 Clinton-Obuchi Joint Statement. Japan's MT-SAT Satellite-Based Augmentation System, which was declared operational in September 2007, is fully compatible and interoperable with GPS. Japan's Quasi-Zenith Satellite System (QZSS), which will improve GPS coverage over Japan, has also been designed to be compatible and interoperable with GPS. The US is working with Japan to set up QZSS monitoring stations in Hawaii and Guam.

The European Union and the US signed a GPS-Galileo Cooperation Agreement in 2004. We jointly designed a new civil signal modulation known as MBOC (multiplexed binary offset carrier) that will be used on both GPS III and the Galileo open service. We also confirmed compatibility and interoperability between the planned signals known as L5 on GPS and E5a on Galileo. Aside from technical cooperation, we have opened channels for bilateral communication on issues related to trade and civil applications, next-generation GNSS, and security. We have started a joint outreach initiative intended to promote the future user benefits of a combined GPS-Galileo service.

Russia and the US have been negotiating a GPS-GLONASS Cooperation Agreement since 2004. Productive technical working group meetings have been held. Russia is considering a proposal for GLONASS to adopt two new civil code division multiple access signals at L1 and L5 which will be interoperable with GPS, supporting an emerging international consensus on use of L1 and L5 for interoperable civil signals.

India and the US have had policy and technical consultations on GPS cooperation underway since 2005. Interoperability between the US government supported wide area augmentation system and India's planned GPS and GEO Augmented Navigation (GAGAN) system based on GPS, has been agreed. The US and India are also discussing greater interoperability between GPS and the planned India Regional Navigation Satellite System (IRNSS). US and India recently conducted a productive GPS-IRNSS interoperability and compatibility working group and an ITU coordination meeting in Bangalore in January of 2008. In addition to Indian efforts, the US also held a GPS policy and technical consultation with Australia in April of 2007 leading to the signing of a joint delegation statement on GPS cooperation.

Multilateral Cooperation

A major recent success in the multi-lateral arena was the creation of the International Committee on Global Navigation

26 June 2004, press conference at US-EU Summit in Ireland (US Secretary of State Colin Powell, Irish Foreign Minister Brian Cowen, EU Vice-President Loyola De Palacio).

Satellite Systems (ICG). The concept for the ICG emerged from the 3rd United Nations Conference on the Exploration and Peaceful Uses of Outer Space and was formally established in November 2006. The ICG is already making significant progress towards the goals of encouraging compatibility and interoperability among global and regional space-based PNT systems and promoting the use of GNSS and its integration into infrastructures, particularly in developing countries. The Indian Space Research Organization (ISRO) hosted the highly successful 2nd ICG meeting at Bangalore, India in September 2007.

The US is also very pleased that a GNSS Providers Forum (PF) has been set up in conjunction with the ICG. PF members consist of global and regional PNT providers: the US, European community, Russia, China, Japan, and India. Providers agreed at the forum meeting at Bangalore, in September 2007, on definitions of compatibility and interoperability that are consistent with those provided above. In addition, the providers agreed that compatibility should also involve spectral separation between each system's authorized service signals and other systems' signals.

The leadership of the United Nations Office for Outer Space Affairs (OOSA) has contributed significantly in the organization of and planning for ICG and PF meetings and functions as the ICG and PF secretariat. Workshops to encourage wider GNSS use in developing countries are supported by US funds, and in some cases by speakers from this office or other USG departments, and have been held in countries as diverse as Malaysia, Colombia, and Zambia.

The next meeting of the ICG and PF will be held at Pasadena, California, 8 to 12 December 2008, and hosted by the NASA Jet Propulsion Laboratory and the California Institute of Technology. Four existing ICG working groups will discuss future plans on: (1) interoperability and compatibility, (2) enhancement of performance of GNSS services, (3) information dissemination, outreach, and education, and (4) interactions with national and regional authorities and relevant international organizations focused on GNSS ground network infrastructure. US GNSS industry and service providers will have exhibits at and participate in parts of the meeting along with worldwide GNSS experts to discuss issues of common interest.

Regional Cooperation

The US is also engaging in regional cooperation on GNSS issues through the Asia-Pacific Economic Cooperation (APEC) GNSS Implementation Team (GIT) activity. This team, made up of the world's fastest growing economies, allows for regular exchange of information on GNSS developments. To date the GIT's focus has been on aviation, with a test bed project coming to successful conclusion this year. A GNSS Innovation Summit will be held in Bangkok, Thailand this month to concentrate on all modes of transportation. There is also interest within APEC to examine the linkages between GNSS and energy efficiency. The US believes that APEC activity on GNSS will add value to ICG developments.

Summary

The US is committed to keeping GPS as a central pillar in an emerging international system of GNSS. Positive results from more than a decade of robust US diplomatic, technical, and operational cooperative efforts on satellite navigation issues are beginning to be seen. New satellite constellations and regional augmentation systems, while independently owned and operated, are being designed to be compatible and interoperable. As these new systems evolve from design to operation, compatibility and interoperability will be the key to "success for all." Our interagency team has achieved initial success in this regard through diplomacy, and diplomatic efforts will continue to be the rule, not the exception, as we navigate our way into a future of ever-expanding space-based PNT capabilities.

Ms. Alice Wong (BS, Mathematics, Pennsylvania State University; MS, Computer Science, American University, Washington, DC) is on a detail assignment as senior aviation advisor for Global Navigation Satellite Systems in the Space and Advanced Technology Office, Bureau of Oceans, Environmental and Scientific Affairs, US State Department. She is responsible for GPS bi-lateral co-operation programs including those with the government of Australia, India, Japan, and Russia. She is also participating in multi-lateral and regional GPS cooperation activities.

Prior to her assignment to the US State Department, she was the program director for the US-China Air Traffic Cooperation Program in the Air Traffic Operations Planning International Office of the Federation Aviation Administration (FAA). She has held senior executive positions in the FAA responsible for communications, navigation, and surveillance requirements implementation for the National Airspace System, system and software engineering, operations research, infrastructure and facility engineering, and telecommunications.

She is a board member of the International Sub Committee of the Civil GPS Service Interface Committee. She reads, writes, and speaks Mandarin fluently.

Mr. Ray Clore (BA, History, Ambassador College, Pasadena, California) has served since 2005 as senior advisor for GPS-Galileo Issues in the US State Department. He served as the science counselor at the US Embassy at Paris from 2000-2004 where he supported the negotiation of the US-EU GPS-Galileo Cooperation Agreement. He has been a career US diplomat since 1977.

Global Positioning Systems: Space-Based PNT for Today and Tomorrow

Col Donald E. Wussler, Jr., USAF
Vice Commander, Global Positioning Systems Wing
Space and Missile Systems Center
Los Angeles AFB, California

The Global Positioning Systems (GPS) Wing, located at the Space and Missile Systems Center, Los Angeles AFB, California, currently supports a worldwide positioning, navigation, and timing (PNT) service to the military operators worldwide and the global civil community. This GPS service is sustained through a robust constellation of up to 32 satellites on orbit, a command and control element providing 24/7 sustainment and anomaly resolution over the entire surface of the Earth, and a military user equipment segment consisting of literally hundreds of thousands of antennas and receiver-processors providing PNT information to end users.

The US maintains a global leadership role in space-based PNT by pursuing its Department of Defense (DoD) military requirements while ensuring the capabilities provided meet the needs of a larger, more "common" segment of the user base, which includes millions of civil and commercial users, in the US and internationally. Imperative to achieving this common denominator approach are the goals of maintaining GPS as a cornerstone of the national PNT architecture and developing a national approach to protect military PNT advantage. The national and international demands of this ubiquitous service drives the GPS Wing to pursue a high operations tempo. Fortunately, the wing is staffed by one of the world's premier acquisition forces covering all aspects of GPS PNT development, sustainment and service. The wing supports the acquisition and launch of several satellites a year to sustain the GPS constellation. In addition, the GPS Wing works with the 50th Space Wing to upgrade the operational control segment to monitor PNT signals to verify service levels and other critical operational parameters.

Through the application of a back-to-basics acquisition approach the GPS Wing is striving to deliver capability to the warfighter by accelerating its development of modernized GPS user equipment and high-accuracy safety-of-life applications. The wing, in consonance with national strategy, will continue to ensure and protect the US military PNT advantage while providing an unrivaled civil PNT service.

The importance of PNT to the national security interests of the US is underscored by the high interest these issues now receive in the federal government. Recently, the assistant secretary of defense for Networks and Information Integration and the under secretary of Transportation for Policy sponsored a national PNT architecture study to provide enhanced PNT capabilities focused on the 2025 timeframe and an associated evolutionary path ahead for government systems and services. This enterprise-level architecture will help achieve the goal of greater PNT capabilities for a broader, more common user community and will enable the evolutionary development of a system-of-systems architecture within the targeted 2025 timeframe.

Figure 1. Next Generation GPS Control Segment.

Since 1983, the US Air Force has provided continuous civilian GPS signals to users worldwide, followed by increased assurance and accuracy as mandated by the Presidential Decision Directive of 1996 that ultimately resulted in the resetting of selective availability to "zero" in May 2000. These provisions and assurance of accurate GPS PNT capabilities have driven increases in international commerce and enabled still-unfolding revolutionary changes in modern warfare.

With the first launch of a GPS Block IIIA satellite in 2014, the GPS constellation will consist of the modernized satellites from Blocks IIR-M, IIF, and III. GPS satellites will then broadcast myriad signals including the new second civil signal (L2C), third civil signal (L5), and the fourth civil signal (L1C) as well as

GPS receivers are being delivered at rates exceeding a million per month. Clearly, GPS has provided an economic engine for the country as the segments that use GPS provide more jobs and increased revenue to Americans.

the military code (M-Code) signal. The new modernized GPS signals will bring significant benefits to GPS users above and beyond the legacy L1 C/A and P(Y) code signals. In addition to the legacy signals, the Block IIR-M satellites all have the new signals, L2C and M-code. The increased signal integrity, PNT accuracy, and heightened security architecture provided by these new signals and improvements will ensure that the GPS system will remain the unrivaled source of space-based PNT. At the time of this writing in March 2008, there are six IIR-M satellites on-orbit within the GPS constellation of 31 satellites. After all eight Block IIR-M satellites are launched and on orbit by 2008, the GPS Wing will begin to launch our next generation of modernized satellites, the GPS Block IIF. This will introduce the new third civil signal, L5, in the aviation-protected spectrum, and will support the increased GPS use planned by the Federal Aviation Administration.

This article, will examine the current state and future prospects of PNT by looking deeper into the influence of space-based PNT on the military and civil user communities. It will cover the provision of timely, relevant, and accurate geospatial intelligence in support of national security objectives by the National Geospatial-Intelligence Agency (NGA), and describe how GPS will play in the international community. Finally, it will look forward to the future technological, leadership, and strategic challenges of space-based PNT in the 21st century.

Figure 2. Future GPS Block IIF satellite.

Influence of Space-Based PNT on the Military and Civil Communities

Today, both military and civilian communities are extremely reliant on GPS as the foundation of additional PNT services. For the military, GPS has become a fundamental and pervasive navigation tool for both air and ground forces. GPS also provides precision, day and night, all-weather guidance and timing to numerous platforms and weapon systems. US and coalition warfighters navigate with GPS across trackless deserts and the open seas. They also employ GPS-guided munitions to maximize military precision attack and minimize collateral damage.

GPS receivers are being delivered at rates exceeding a million per month. Clearly, GPS has provided an economic engine for the country as the segments that use GPS provide more jobs and increased revenue to Americans. Many civil and military systems have developed applications that build upon GPS to provide added services. In general, these systems improve capabilities such as accuracy and integrity of the basic signal. GPS augmentation services span the gamut from precision agriculture to precision aviation. GPS augmentations have spread throughout the world. Many corporations have adopted GPS as an enabler to improve their performance while other corporations are completely reliant on GPS to deliver their products or services.

In addition to automobile and handheld consumer devices, GPS has become the commercial mainstay of transportation systems worldwide, providing navigation for aviation, ground, and maritime operations. Farmers use precision navigation through GPS and an augmentation system to plow, cultivate, and harvest their fields. Surprisingly to many people, auto-pilot assisted/controlled vehicles will probably be realized in the near future. Civil aviation is continuously increasing its reliance on satellite-based navigation in preparation for the expected increase in air traffic. Aircraft can actually fly user-specified routes from point-to-point with reduced dependency on ground infrastructure, resulting in enhanced landing approaches. The potential savings from these improvements to civil aviation stem from increased efficiency of the air traffic control infrastructure. Life-saving missions, including disaster relief and emergency services currently depend on GPS for locating victims and deploying resources. The potential savings in human life and

resources worldwide are astounding. Even everyday, commonplace activities such as banking, mobile phone operations, and control of power grids are facilitated by the accurate timing provided by GPS.

Provision of Geospatial Intelligence: National Geospatial-Intelligence Agency

The NGA is tasked with providing timely, relevant, and accurate geospatial intelligence in support of national security objectives. Geospatial intelligence (GEOINT) refers to the exploitation and analysis of imagery and geospatial information to describe, assess, and visually depict physical features and geographically-referenced activities on the Earth. GEOINT products are composed of imagery, imagery intelligence and geospatial (mapping, geodesy) information. GEOINT can provide situational awareness for making decisions (mission planning) and supporting operations (bombs on target, search and rescue, etc.).

A key component of GEOINT is an accurate geographic location referenced to a standard reference frame. NGA developed and maintains the World Geodetic System 1984 (WGS 84) which is the reference system used for all DoD operations and also provides the common foundation for all geospatial information, whether used for navigation or Earth-science applications. Utilizing the ten NGA and six USAF GPS monitor stations, the WGS 84 reference frame is "tied" to the physical Earth. A more detailed description of NGA's role in GPS and GEOINT can be found in the article in this issue by VADM Robert Murrett, the director of the NGA.

GPS and the International Community

The international PNT policy of the US is driven by two presidential directives. In 1996, the US Global Positioning System Policy introduced GPS as a dual use system and presented a vision for the use of GPS "… to support and enhance [national] economic competitiveness and productivity while protecting US national security and foreign policy interests."[1] In response to changing international conditions and worldwide growth of GNSS applications based on GPS, the US Space-Based Positioning, Navigation, and Timing Policy of 2004 established two overarching PNT goals for the US: remain the pre-eminent military space-based PNT service and remain an essential component of international PNT services.[2]

For the wing, achieving these goals in the international arena requires the US to work within the framework of the international legal system and to negotiate with the administrators of foreign PNT services. Legally, the International Telecommunication Union (ITU), headquartered in Geneva, Switzerland is the lead United Nations agency for information and communication technologies, including Radionavigation Satellite Service (RNSS) PNT systems. International radio spectrum law is embodied in the ITU-R radio regulations. Significantly, the US affords the radio regulations treaty status, so they place restrictions on spectrum-dependent systems, and by US policy the regulations must be adhered to. Additionally, other member nations of the ITU afford the radio regulations similar status and authority.

In the international PNT environment, the most important issue the wing currently faces is the increasing number of RNSS-capable systems being constructed by other nations and entities. As noted above, the president's PNT policy of 2004 requires the GPS to maintain its position as the pre-eminent military space-based PNT service and remain an essential component of international PNT services. Both of these goals are facing new and growing challenges. As recently as 10 years ago, the only operable RNSS constellations in Earth orbit were fielded by the US and the Russian Federation (GPS and GLONASS, respectively). That situation is changing, and the available orbital slots and electromagnetic radio frequency spectrum are becoming increasingly crowded environments.

In addition to the US, six other countries (including the European Union) are developing major RNSS systems. To satisfy the presidential national policy goals while maintaining good relations with foreign RNSS operators, the US has established written agreements with several administrations and maintains open channels of communication with all operators. The specifics of these agreements are handled by the Engineering Division

Figure 3. Modernized GPS user equipment will enable the Air Force to meet the growing needs of military and civil users worldwide.

of the GPS Wing at the Los Angeles AFB Space and Missile Systems Center. At this time, the wing believes that US relations with the administrators of the foreign PNT systems are positive, and looks forward to continued mutually beneficial relationships.

Future Technological, Leadership and Strategic Challenges

Space-based PNT has revolutionized military operations, air traffic control, commercial navigation, timing of financial transactions, and so forth. The list is potentially endless as demand and utilization continue to grow. However, new and significant vulnerabilities also exist and continue to grow. Further, demand for even greater availability and integrity is increasing. Due to the pervasive use of GPS, a cogent strategy is required to ensure that GPS will address vulnerabilities, meet demands, and facilitate integration with other GNSS systems.

Three fundamental imperatives at the core of GPS' strategic vision are to sustain the constellation (24 operational satellites must be available on orbit with 95 percent probability averaged over any given day), modernize GPS capability to address vulnerabilities and keep pace with the ever-growing PNT demands of warfighters, civil, and commercial users, and to support vital US PNT policy goals and international commitments.

In support of GPS availability commitments, Block IIF satellites will begin to launch in 2009 and Block III satellites will begin to launch in 2014. The wing's strategy is to integrate all three segment developments (space, control, and user) so capability reaches the warfighter sooner and in a more synchronized manner. Hence, the GPS Wing anticipates no more aging of satellites and control while waiting for military user equipment to be developed. The wing, working with its partners at Headquarters Air Force Space Command and the Air Staff, has solidified the GPS Enterprise programming and budgeting process to ensure the stability required to move all three segments forward together.

To successfully execute developments across the three GPS segments (i.e., space, control, and user), the GPS Wing has reinvigorated systems engineering in its space systems acquisition. In particular, the wing has reemphasized integrated product teams with matrixed support for enterprise processes (i.e., financial management, contract management, configuration management, risk management, etc.) and enterprise functions, such as security, test, systems engineering, and system integration.

The wing has also established and maintained a stable business rhythm built on executable schedules using disciplined processes. The GPS Wing's strategic direction has been created and socialized with stakeholders. From an outreach perspective, the wing has re-established the GPS Partnership Council, bringing together its US national partners.

Conclusion

It's clear that the US will continue to face new challenges in pursuit of its overall objective of maintaining a global leadership role in the provision of accurate PNT services. There are many examples of the broad and deep penetration of PNT technology in the military and civil fields, and its critical importance in the provision of geospatial intelligence, a field that occupies the intersection between scientific advancement and national security concerns. With respect to future PNT prospects and challenges, it's obvious the US has an outstanding GPS service record on which to build: since December 1993, the US government has met or exceeded civil GPS service performance commitments, and the US DoD remains committed to superior GPS service. The men and women of the GPS Wing look forward with confidence to fulfilling its mission of providing accurate PNT for the US, while simultaneously pursuing mutually beneficial relationships with other nations also participating in this vitally important field.

Notes:

[1] US Global Positioning System Policy, fact sheet, 29 March 1996.

[2] US Space-Based Positioning, Navigation, and Timing Policy, fact sheet, 15 December 2004.

Col Donald E. Wussler, Jr., (BS, Mathematics, University of Notre Dame; MS, Systems Management, Air Force Institute of Technology; MS, National Resource Management, Industrial College of the Armed Forces) is vice commander, GPS Wing, Space and Missile Systems Center, Air Force Space Command, Los Angeles AFB, California. He is responsible for a multi-service, multinational systems wing which conducts development, acquisition, fielding, and sustainment of all GPS space segment, satellite command and control (ground) segment, and GPS military user equipment. The $32 billion GPS program, with a $1 billion annual budget, maintains the largest satellite constellation and the largest avionics integration and installation program in the Department of Defense.

Colonel Wussler was commissioned through ROTC upon graduation from the University of Notre Dame in 1983. His assignments include the Aeronautical Systems Division, two tours at the Electronic Systems Center, and Headquarters United States Air Force. He has been responsible for the acquisition and programming for such systems and technologies as United States AWACS, Air-to-Air Combat Identification, Theater Air Control Systems, and United States and NATO Joint STARS. Additionally, Colonel Wussler has represented the Air Force with the House and Senate Appropriations Committees for all Tactical Air, Weapons, Science and Technology and Test and Evaluation Programs, to include the F/A-22, AMRAAM, JASSM, and C2 aircraft. He also served as system program director for Force Protection Command and Control Systems. Prior to assuming his current position, Colonel Wussler was commander, Counterspace Group, Space Superiority Systems Wing, Space and Missile Systems Center, Los Angeles AFB, California.

Military Positioning, Navigation, and Timing: **Strategic Challenges and Opportunities**

Lt Col Jon M. Anderson, USAF
Student, Naval War College
Newport, Rhode Island

Positioning, navigation, and timing (PNT) is a term rarely used outside of the US government, but usefully consolidates, under one banner, the various systems, policies, and activities concerned with providing positioning information, navigation capabilities, and time dissemination. By most measures, PNT is a thriving, healthy, global enterprise, largely due to the Global Positioning System (GPS). Provided by the US as a free global utility, the worldwide market for GPS-based products exceeds $30 billion.[1] GPS is a national asset, a tangible symbol of US economic and military might that has been so brilliantly successful, and so universally adopted, that Russia, the European Union (EU), and China have all developed GPS imitations, and are in various stages of deploying them, while more than 50 nations have developed GPS augmentations. In many ways, GPS was the very first truly global utility, and its potential is only now being realized as new commercial applications emerge every year. Although the GPS program faces its own set of unique problems and challenges, these are part of the normal ebb and flow of managing and operating a complex system, and are not the subject of this article.

Positioning, Navigation, and Timing Challenges

The Joint Capabilities Document (JCD) for PNT, developed by US Strategic Command (USSTRATCOM), states that "no other capability permeates the fiber of joint operations like PNT."[2] Although GPS is not the sole source of PNT for the US military, it is the primary source for most users. Compared to the next best alternatives, GPS is inexpensive, reliable, and highly accurate. It has changed not only how US forces navigate, but how they fight. Like their civilian counterparts, the Soldiers, Sailors, Marines, and Airmen of the US armed forces take the availability of GPS for granted, experience having taught them that GPS works nearly everywhere and nearly all of the time. Most PNT challenges are therefore GPS challenges—its limitations and its vulnerabilities. Some of these challenges have known solutions, but lack sufficient funding or support within the Department of Defense (DoD). Some may be partially solved with emerging technologies. Others may be intractable, whether due to physics or budgets. Most have been identified, in various fashions, by the numerous studies, reports, reviews, panels, and boards that have examined the state of PNT during the past two decades. What follows is a strategic survey of three major challenges, and some potential opportunities for addressing them.

Challenge 1: The Availability of PNT

Although eminently functional in most environments, GPS does have its limitations. GPS signals are very weak, on the order of a femtowatt and are easily blocked by obstructions such as buildings and terrain.[3] The signals do not penetrate underwater or underground. They are vulnerable to radio frequency (RF) interference, both intentional and unintentional. The accuracy of the time or position obtained by the GPS user is directly related to the geometric relationship between the user and the visible satellites, resulting in degraded performance whenever a portion of the sky is obscured. As a result of these factors, the PNT JCD identified several primary PNT gaps, including access to PNT in the presence of "geospatial impediments," which includes environments such as indoors, underwater, underground, and both natural and urban canyons.[4]

Several prominent advisory groups have examined the problem of availability, including the Defense Science Board, the GPS Independent Review Team, and the National PNT Advisory Board. Given the considerable overlap in membership between these groups, it is unsurprising that a common solution to availability issues has emerged. All have recommended increasing the baseline GPS constellation size to 30 satellites, from the current nominal 24-satellite constellation.[5] While this solution can improve the availability of satellites when visibility is partially constrained, maintaining a minimum of 30 GPS satellites does not solve the problem for the more severe capability gaps, such as indoors, underwater, and underground. Nor is it clear that actual accuracy requirements in urban and natural canyons can bet met by merely increasing the number of available satellites. In many cases, more satellites may increase the probability of a "fix" without providing sufficient improvement to the geometry that determines positioning accuracy, a critical factor for applications such as targeting.

This does not negate the value of a 30-satellite constellation. Military and civil users have become accustomed to 29 or 30 satellites for several years, and returning to a 24-satellite constellation, which although it meets minimum specifications, would represent a significant degradation in actual performance. Raising the guaranteed constellation size may also

The Joint Capabilities Document for position, navigation, and timing states that "no other capability permeates the fiber of joint operations like position, navigation, and timing."

Although there is no accurate information on how many commercial GPS handheld units are used by troops deployed to Iraq and Afghanistan, there is abundant anecdotal evidence that points to widespread use of GPS handhelds in military operations.

allow reduced aircraft separation, which would improve air traffic management and save fuel.[6] And a larger constellation, with optimized satellite placement, could provide improved performance in some parts of the Earth, such as the Arctic and Antarctic regions.[7] Yet a 30-satellite constellation does not address the primary PNT gaps identified in the PNT JCD. In fact, most of these gaps will not be met by GPS alone, if at all.

Challenge 2: The Security of PNT

Unlike inertial navigation systems and local timing sources, PNT users who are dependent on GPS must rely on external radio signals. As with radar and communications, these signals can be jammed by adversaries in a variety of ways, leading the original GPS developers to incorporate secure encryption and anti-jam features into the design. The secure military signal, known as P(Y)-code, is used by the US military, some federal agencies, and the military services of several allied nations. In addition to providing an element of assurance to the military user, the P(Y)-code signal is more resistant to jamming than the civil (C/A-code) signal, and military users have access to two frequencies, rather than the single frequency available to civil users today. The use of encryption also creates a form of military exclusivity, which provides a uniquely available signal to authorized users, although many high precision commercial receivers utilize techniques that exploit general characteristics of the military signal while ignoring the encryption. Growth in applications based on these techniques has led to a commitment by the government to maintain the characteristics until a second coded civil signal is available from the GPS constellation.

Anti-jam for GPS users exists in several forms, from natural body masking on aircraft and terrain masking for ground users, to technical innovations such as adaptive antenna arrays, narrowband frequency filters, and "tight" integration with inertial sensors. Military GPS receivers are designed to operate under jamming conditions and are generally more robust. These military receivers also typically utilize older technology than modern commercial GPS receivers due to the much faster commercial product cycle time and additional unique requirements levied upon military electronic equipment. High end systems, used on military aircraft, ships, and some missiles and munitions, are typically part of an integrated navigation system, and often operate outside of the range of the most likely threat, which is ground-based jamming. In recent years, attention has mainly focused on low-end users, especially military handheld GPS receivers, which are also widely used in vehicles. For these users, size, weight, and cost are critical factors, and anti-jam techniques that are practical for aircraft have limited utility. Military receivers are far more expensive than most off-the-shelf GPS handheld units, leading to one of the emerging issues for military PNT: the use of commercial GPS handhelds.[8]

Commercial GPS receivers are inexpensive, user-friendly, and readily available. Although there is no accurate information on how many commercial GPS handheld units are used by troops deployed to Iraq and Afghanistan, there is abundant anecdotal evidence that points to widespread use of GPS handhelds in military operations.[9] One manufacturer even provides testimonials from soldiers on its website,[10] indicating that commercial GPS receivers are not only widely used, but that they are very useful in day-to-day military operations.

There is no reason to doubt the wisdom of commanders who authorize or encourage use of commercial GPS receivers. If each soldier could be equipped with a military equivalent, there would be no cause to resort to the commercial alternative. From a strategic perspective, though, two issues have emerged from this practice. First, in the absence of significant threats to GPS, units have found the commercial alternative reliable and useful. Since the troops are "getting by" with the use of commercial GPS, there is no pressure from operational commanders to provide adequate funding for secure GPS, leaving US forces vulnerable to emerging threats, should they manifest. Second, the widespread dependence on civil GPS signals restricts the freedom of commanders to employ local denial options against enemy GPS use, the subject of the third PNT challenge.

Challenge 3: Universal Access to PNT

Like cell phones, computers, and the Internet, GPS is used worldwide, by ordinary citizens and military forces of both our allies and our adversaries. From its inception, military leaders have been concerned about universal access to the precise PNT that GPS can provide. In addition to encrypting the military signals to provide exclusivity, GPS originally included a method for limiting the performance of the civil signal. This technique, known as selective availability (SA), proved too hard to bear for the US government and so has been eliminated. Today there is little difference in the accuracy available to US forces and their enemies.

On 27 September 2007, the White House announced that SA would no longer be included in future GPS satellite procurements.[11] This came seven years after SA was effectively disabled ("set to zero"), and 11 years after the White House first directed the DoD to seek alternatives.[12] The concept behind SA was to use positioning and timing accuracy as a discriminator between military and civil users. The signal was intentionally degraded, a condition that could be removed by authorized users with a valid decryption key. Not only was this enormously unpopular with the civil GPS community, it was easily circumvented by differential techniques. The Department of Transportation (DoT) funded and developed differential GPS, leading to the untenable situation where one arm of the federal government was undermining another. The White House, in

the Presidential Decision Directive (NSTC-6), directed DoD to protect US military use of GPS in the presence of jamming, develop the means to prevent the use of GPS by adversaries, and ensure that civil users outside of the area of military operations would be unaffected.[13] This initiative was commonly known as navigation warfare (Navwar). Although elements of Navwar already existed, the three tenets (protection, prevention, preservation) embodied the notion that GPS was outgrowing the security features embedded in its design, and a different approach was needed, one that did not include SA. The Navwar tenets were further codified in direction from Congress in Title 10, USC,[14] and the White House 2006 policy on space-based PNT.[15]

The only practical method of denying use of GPS to an enemy while limiting the effects to a geographical region is to employ local electronic warfare (EW). Unfortunately, the GPS civil and military signals share the same frequency range. Although the military originally enjoyed access to a second frequency unencumbered with a civil signal, pressure from civil agencies led to this frequency becoming dual-use as well. After searching for a tractable solution that would enable military use of GPS in the presence of "friendly" jamming of the civil GPS signal, the Air Force developed a new military signal, M-Code, which shares the current GPS frequencies, yet is sufficiently separated from the civil signal to provide secure GPS to military users in the presence of Navwar prevention operations.

M-Code offers several advantages in addition to "spectral separation." Its design increases the accuracy and jamming resistance of the military signal, and it includes several enhanced security features. As of this writing, six M-Code capable satellites are on-orbit, and receiver development is rapidly maturing, although receivers are not yet in production. However, even with the most optimistic projections, M-Code capable receivers will be in the minority for at least a decade, if not longer. The DoD has invested heavily in current GPS capability, and these systems will be replaced by attrition, which could mean a sizable minority of legacy GPS receivers for the next 20 to 30 years. The problem is further compounded by the large number of commercial receivers used by military forces. To date, the threat of adversary GPS use has not emerged in a direct way that justifies the operational cost of using denial techniques, leaving the issue dormant for nearly a decade.

Opportunities

No single solution exists for these three challenges, although many solutions address all three to some degree. Several opportunities are already available, while some will require further investment. The three issues of availability, security, and exclusivity are fundamental to GPS, but improving GPS itself is only a first step.

GPS Modernization

GPS modernization includes the addition of new civil signals, improvements to the accuracy and integrity of the system, and a new military signal. The next generation of GPS satellites, GPS III, will include higher power M-Code signals, which will improve both reception in the presence of interference and operation in some impeded environments. Given the high cost of improving the space segment, as well as the long time horizon required for implementing new capabilities, GPS III represents the effective end-state for the GPS space segment and further improvements are too far in the future to consider as opportunities.

Perhaps the most significant aspect of GPS modernization for military PNT is the migration to modernized military GPS user equipment (MGUE), comprising new equipment designs which will be necessary to benefit from spectral separation, higher security, and higher-power signals. DoD policy requires certain categories of military users to upgrade to MGUE by the time the 24th M-Code capable satellite is operational,[16] or approximately 2014. Congress appears to be supporting this policy, increasing MGUE funding by $63.9 million in the fiscal year 2008 budget.[17] The most essential requirement for MGUE migration is for the military services to program funds for MGUE procurement during the next 10 years. To curb the growing use of commercial GPS receivers by US forces, a low-cost MGUE variant is needed. Achieving this may require very large procurements to reduce the unit cost or a major capital investment by DoD.

Military GPS Augmentations

Although generally operating in more benign environments, civil GPS users enjoy a wide variety of capabilities unavailable to most military users. This is in spite of civil dependency on a single GPS frequency and a weaker signal structure. To identify potential solutions to military PNT challenges, it is useful to examine how GPS civil users have overcome its shortcomings during the past two decades.

For many applications, civil requirements are far more stringent than for the military. Centimeter-level accuracy for surveyors and precision farming, six-second anomaly reporting for aviation safety-of-life, and indoor mobile phone location are some of the services that standalone GPS cannot meet. Although many civil augmentations to GPS were developed when SA was the primary source of positioning error, they continue to be widely used due to the improvements in accuracy and integrity they offer. DoT's National Differential GPS system includes 39 coastal stations and 38 inland stations in the US, and can improve GPS accuracy to less than one meter.[18] Similar systems are operated worldwide by 50 countries. The International GNSS Service (IGS) operates more than 400 monitoring stations worldwide that track GPS and other satellite navigation systems and provide accurate orbital and timing data for precision users,[19] albeit not typically in real time.

The Federal Aviation Administration operates the Wide Area Augmentation System (WAAS), which utilizes geostationary satellites and a network of ground stations to provide differential corrections and integrity warning to much of North America. Similar systems are being built by the EU, India, and Japan, and even more advanced space-based augmentation systems (SBASs) are in development, including Japan's Quasi-Zenith Satellite System (QZSS).[20] NavCom Technology's Starfire

DoD lacks the institutional structure for evaluating promising PNT enhancements, conducting a comprehensive cost/risk assessment, choosing the best value for the warfighter, and developing an operational capability.

network is a prime example of a successful commercial SBAS, providing 10 cm accuracy to subscribing users worldwide.[21]

Augmentation systems for military PNT have been widely studied, but development has been limited. The Talon NAMATH (TN) program, developed as an Air Force experimental capability, improves GPS accuracy by providing the accurate orbital and clock data available at the GPS master control station to worldwide users via a secure DoD network.[22] TN may be upgraded to improve anti-jam in some receivers, by enabling a technique known as "data-stripping." The primary limitation of TN is connectivity; users must have a means of loading the data in GPS receivers, by tactical datalinks or other means. This limits its utility for handheld and vehicle mounted GPS users.

Pseudo-satellites (pseudolites) are ground, sea, or air-based transmitters that transmit GPS-like signals, usually at far greater power than the GPS satellites. Several pseudolite programs have been tested, notably by the Defense Advanced Research Projects Agency (DARPA) with its Global Positioning Experiments (GPX) program. GPX employed airborne pseudolites and demonstrated positioning for users on the ground in very high levels of jamming, although with degraded accuracy.[23] Once testing was complete, DARPA was unsuccessful in gaining traction within DoD to continue development of GPX.

One military augmentation system that has gained recent attention within DoD is Boeing's "iGPS" program, which uses the Iridium constellation of 66 low-Earth orbit (LEO) satellites to integrate communications and navigation and provide accurate ephemeris and clock data as well as enhanced anti-jam capability for users equipped to receive both GPS and Iridium signals. DoD requested \$81 million for iGPS in the fiscal year 2008 budget, which was denied by Congress.[24] However, Congress did approve \$10 million for further concept development, and the Navy has requested \$61 million in FY09 for iGPS receiver development.[25] Although the concept is technically promising, it requires new receivers that integrate GPS, Iridium, and an inertial measurement system, as well as a US government commitment to bear some or all of the cost to sustain the Iridium constellation.

Together, GPX and iGPS illustrate the primary challenge in developing joint GPS augmentation systems for military PNT. Unlike GPS satellites, ground control systems, and user equipment, there is no budget line item, program office, or agency responsible for augmentations or for integration of separate PNT capabilities into production military GPS equipment. DARPA effectively matured their GPX concept, and some of the results have been incorporated into GPS systems engineering documents. But there was no home within DoD for pseudolites. On the other hand, iGPS obtained traction due to Boeing's aggressive marketing to decision makers in DoD, a strategy that proved effective. However, it requires the continued support of its DoD champions, which in the normal cycle of retirements and new appointments may not endure. DoD lacks the institutional structure for evaluating promising PNT enhancements, conducting a comprehensive cost/risk assessment, choosing the best value for the warfighter, and developing an operational capability. Instead, PNT enhancements tend to be point solutions for specific users or demonstration projects that never become programs. The few exceptions, such as TN and GPS modernization, are Air Force Space Command (AFSPC) projects, with associated program elements and major command advocates.

Perhaps the best approach for demonstrating and evaluating potential military PNT augmentation systems is through joint experimentation. GPS augmentations are not typically dependent on advanced technology, but on systems integration. Nor are they service-unique. The advantage of joint experimentation is that the focus is on near-term solutions and leveraging existing capabilities. Fortunately, a suitable organization already exists with the appropriate charter and expertise for joint PNT experimentation, the Joint Navigation Warfare Center (JNWC). The JNWC was established in 2004 by the deputy secretary of defense under USSTRATCOM, and has extensive experience in GPS testing. Expanding the JNWC's role to include experimentation with solutions to the primary PNT gaps would require only a modest increase in funding, certainly less than the \$81 million the DoD originally planned for iGPS.

As GPS dependence has grown, the civil PNT community has explored suitable backup systems, should GPS become unavailable. This is particularly a concern for safety-of-life applications, such as aviation. It is also particularly difficult, since GPS is unique in enabling, in one signal set, determination of the three dimensions of position, as well as precise time. The leading candidate appears to be enhanced long-range navigation (eLORAN), which is an upgrade to LORAN-C. eLORAN will enable two-dimensional position determination to an accuracy of 10-20 meters, and utilize a low frequency, high power signal.[26] A similar system, deployable and with sufficient security enhancements, could be the basis for a local military PNT capability that would work in many of the impeded environments that prohibit GPS use. Another concept that has been explored within DoD is the use of network-assisted GPS, which uses techniques similar to cellular phone networks and the E911 system. Integrating communications and navigation is one of the most effective means of enhancing GPS. A "connected" GPS receiver can receive encryption keys, satellite data, and timing information; it can also report its position to commanders and cooperate with other PNT users to improve positioning accuracy. Even a relatively low-bandwidth, low-cost data link in a GPS receiver would be sufficient for using TN, transmitting keys, or reporting position. As with GPS augmentations,

these would be suitable areas for joint experimentation by the JNWC.

Technology Enhancements

Emerging technologies such as the chip-scale atomic clock (CSAC) and the micro electro-mechanical systems inertial measuring units (MEMS IMUs) will likely improve the capabilities of both GPS and autonomous PNT. The Navy's "Navigation Nugget" uses both technologies, integrated with a GPS receiver.[27] The CSAC and MEMS IMU provide accurate time and motion sensing, which can aid a GPS receiver in maintaining signal lock in the presence of jamming. The Army has also evaluated various technologies to enhance urban and indoor PNT, including MEMS IMUs, enhanced dead reckoning systems, network-assisted GPS, scene matching, and local RF ranging systems.[28] The "holy grail" for autonomous PNT is a system that can provide sufficient accuracy for several hours without requiring a GPS fix, thus enabling PNT in some of the more difficult environments, such as underground, indoors, and underwater.

Responsibility for development, acquisition, and procurement of PNT systems resides in the Air Force, Navy, and Army acquisition centers. Although the GPS Wing, part of AFSPC, is primarily responsible for GPS security and MGUE development, PNT solutions are primarily the responsibility of individual programs. For integrated communications and navigation, or PNT augmentation systems, there is no single organization responsible for developing user PNT systems, which are increasingly embedded applications, rather than standalone devices. Organizational roles and responsibilities need to be clarified within DoD, especially for development of integrated communications/navigation and blended sensors.

Galileo

The Defense Science Board recommended in 2005 that military GPS user equipment exploit all available signals to improve accuracy, robustness, and integrity.[29] Europe's Galileo system, currently under development, utilizes two of the same frequencies as GPS, including the primary frequency, known as L1. The US government, led by the State Department, but with technical expertise provided by AFSPC, has exerted enormous efforts to ensure both compatibility and interoperability between GPS and Galileo. Even while the National PNT Advisory Board recommends 30-plus GPS satellites to improve geometry and provide better accuracy for military users in urban/natural canyons, there are no plans to include Galileo capability in future military receivers. If Galileo achieves its goal of 30 satellites, the combination of GPS and Galileo may exceed 60 satellites, allowing near optimal geometry for most users. Military users could include Galileo satellites as an "augmentation" to GPS for accuracy improvement, while still relying on the GPS M-Code as the primary source for secure PNT. Former National Security Space Office director Maj Gen James B. Armor, USAF, retired, went even further when he suggested the US should offer to have the EU operate and build GPS satellites, yielding a jointly managed constellation.[30] This approach would easily yield 40 to 50 satellites, at lower cost for both the US and the EU, but would require a significant change in US PNT policy.

Navstar GPS IIF.

Electronic Warfare

For the Air Force and the Navy, EW has traditionally focused on suppression of enemy defenses (SEADs) and communications jamming, utilizing low-density, high-demand assets.[31] Such systems are high-power, broad-area jamming systems, possibly unsuitable for Navwar prevention, where signal fratricide is a critical concern. A new opportunity has emerged from recent operations in Southwest Asia. The deployment of more than 30,000 jammers to Iraq and Afghanistan to combat the improvised explosive device (IED) threat awakened the Army and the Marine Corps from their decades-long neglect of EW.[32] As a result, the Army has created an EW Doctrine Center,[33] and the Marine Corps has revisited its EW vision, transforming from platform-centric jamming to distributed capability.[34] Unlike traditional SEAD assets, the large number of lower-power jammers, deployed with ground units, and the associated tactics that have been developed to minimize harm to friendly users have created a potential opportunity. Combined with effective modeling tools, it may be possible to develop Navwar tactics that utilize space and time to control effects, limiting both signal fratricide against military users and undesirable impact on civil users. Incorporating land-based EW into joint training, exercises, and experimentation will aid in developing tactics, techniques, and procedures for Navwar prevention operations.

Conclusion

According to Kinkler's Second Law, "all of the easy problems have been solved."[35] The PNT capability gaps exist because they are hard problems, subject to physical and budgetary constraints. Along with other information technologies, PNT capabilities will continue to proliferate, leveling the playing field between the US and its potential adversaries. Although it is tempting to wait for future technology to fill PNT gaps, there is no assurance that technology can solve these problems affordably.

Developing PNT augmentations, effectively using existing technologies, integrating the most useful and promising with GPS, and increasing joint experimentation can all contribute to filling the PNT capability gaps in the near term, and ensuring that the US remains ahead of the pack in military PNT.

Notes:

[1] Jayashree Adkoli, "Research Firm Predicts GPS Market will Reach $30 Billion by 2008," 11 December 2007, http://www.tmcnet.com/voip/ip-communications/articles/16261-research-firm-predicts-gps-market-will-reach-30.htm.

[2] United States Strategic Command, *Joint Capabilities Document for Position, Navigation, and Timing*, 28 September 2006, 4.

[3] Mark C. Crews, "Global Positioning System International Challenges and Opportunities in the 21st Century," *High Frontier* 3, no 2 (March 2007): 38.

[4] *Joint Capabilities Document for PNT*, 13-14.

[5] Meeting Minutes, National Space-Based Positioning, Navigation, and Timing (PNT), Advisory Board, 4-5 October 2007, 7-8.

[6] Ibid., 20.

[7] Ibid., 8.

[8] The GPS Wing has produced a comprehensive video outlining the dangers of commercial use of GPS. http://www.archive.org/details/GPSwarfighter

[9] As a student at the Naval War College, the author has had numerous interactions with Army and Marine battalion commanders recently returned from Afghanistan and Iraq. All stated that they nearly always carried commercial GPS receivers with them during operations, as did most of their troops.

[10] Garmin, Your Garmin, Your Story, http://www8.garmin.com/products/rino/testimonial.html.

[11] The White House, Statement of the Press Secretary, http://www.whitehouse.gov/news/releases/2007/09/20070918-2.html, 18 September 2007.

[12] Presidential Decision Directive NSTC-6, The White House, 28 March 1996, http://www.fas.org/spp/military/docops/national/gps.htm.

[13] Ibid.

[14] US Code Collection, Title 10, Subtitle A, Part IV, Chapter 136, § 2281, http://www4.law.cornell.edu/uscode/html/uscode10/usc_sec_10_00002281----000-notes.html.

[15] US Space-based Positioning, Navigation, And Timing Policy, fact sheet, 15 December 2004, http://pnt.gov/policy/..

[16] ASD/NII memorandum, "Global Positioning System User Equipment Development and Procurement Policy," 7 August 2006.

[17] "Congress Pares GPS III Funds, Slams Air Force Space Acquisition Efforts," *Inside GNSS News*, 28 November 2007, http://www.insidegnss.com/node/393.

[18] National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board, meeting minutes, 18.

[19] Ibid., 6.

[20] Space-Based Positioning Navigation and Timing, National Executive Committee, GPS Augmentation Systems, http://pnt.gov/101/augmentations.html.

[21] NAVCOM, The Star Network, basics, http://www.navcomtech.com/StarFire/.

[22] Michael A. Mras, "Air Force Tactical Exploitation of National Capabilities," *High Frontier* 4, no 2 (February 2008): 35-36.

[23] Maryann Lawlor, "Researchers Locate Satellite Options" http://www.afcea.org/signal/articles/anmviewer.asp?a=480&print=yes, November 2001, *Signal Magazine*.

[24] Sebastian Sprenger, "i-GPS Plan Stumbles on Capitol Hill," *Federal Computer Week*, 4 June 2007, http://www.fcw.com/print/13_18/news/102863-1.html.

[25] *The Insider*, report on the Defense Department, Congress and the defense industry, 12 February 2008, http://defense.iwpnewsstand.com/insider.asp?issue=02122008.

[26] Meeting Minutes, National Space-Based PNT, 17.

[27] Randy Rollo, "Navigation in a Nugget: SPAWAR Leverages New Chip-Scale Atomic Clock," *GPS World Military & Government*, 1 September 2007, http://mg.gpsworld.com/gpsmg/Warfighter/Navigation-in-a-Nugget/ArticleStandard/Article/detail/458589?contextCategoryId=25182.

[28] Paul Olson, "US ARMY CERDEC/C2D Program in Urban/Indoor Positioning and Navigation," Precision Personnel Locator Project Workshop, 7 August 2007, 7.

[29] Defense Science Board Task Force on the Future of the Global Positioning System, October 2005, 18.

[30] Don Jewell, "Leadership Talks—PNT Architecture from the Top," *GPS World*, 1 September 2007, http://mg.gpsworld.com/gpsmg/article/articleDetail.jsp?id=452348.

[31] John A. Tirpak, "Where Next With Electronic Attack?," *Air Force Magazine* 89, no 10 (October 2006): 30-31.

[32] Nathan Hodge, "US Military Looks to 'Offensive' Focus in Counter-IED Fight," http://www8.janes.com/.

[33] Stephen Trimble, "US Army Moves Back Into Electronic Attack Mission," *Jane's Defence Weekly* http://www8.janes.com/.

[34] Richard R. Burgess, "Jamming: The Marine Corps Refines Its Vision of Electronic Warfare," *Sea Power* 50, no 12 (June 2007): 22.

[35] bbc.co.uk, guide entry, Jester's Condescending English Dictionary - K, http://www.bbc.co.uk/dna/h2g2/A427925.

Lt Col Jon M. Anderson (BS, Electrical Engineering, University of Kansas; MS, Electrical Engineering, South Dakota School of Mines and Technology; PhD, Electrical Engineering, Air Force Institute of Technology) is currently a student at the Naval War College in Newport, Rhode Island. Commissioned through ROTC in 1988, his first assignment was as a missile launch operator at the 44th Strategic Missile Wing at Ellsworth AFB, South Dakota. From 1993 to 1996, he served as a Future Radar Systems analyst at the National Air Intelligence Center at Wright Patterson AFB, Ohio. His next assignment was at the GPS Joint Program Office in Los Angeles, where he was chief engineer for Navigation Warfare and GPS Modernization, and led the engineering team that developed the next generation military signal. After attending AFIT from 1999 through 2001, he served for two years as a technical advisor at the Air Force Operational Test and Evaluation Center at Kirtland AFB, New Mexico. In 2004, Colonel Anderson was assigned to the Directorate of Space Acquisition, Office of the Undersecretary of the Air Force, where he served as the principle action officer for positioning, navigation, and timing policy issues at Headquarters Air Force. Colonel Anderson has been awarded the Defense Meritorious Service Medal, Air Force Meritorious Service Medal and the Air Force Commendation Medal with oak leaf cluster, the Air Force Achievement Medal, and was a recipient of the Arthur Flemming Award in 1998. He is a graduate of Squadron Officer School, Air Command and Staff College, Air War College, and the Air Force Institute of Technology.

Controlling GPS: Architecture Evolution Plan and Beyond

Lt Col Harold W. Martin III
AFSPC Command Lead, PNT Programs
Peterson AFB, Colorado

Mr. Walter Petrofski
GPS Project Lead
SI International
Peterson AFB, Colorado

The Global Positioning System (GPS) has revolutionized navigation, military maneuver, and commercial transportation and is now transforming information infrastructures around the world. Originally, GPS was designed as a dual-use system with the primary purpose of enhancing the effectiveness of US and allied military forces. Since it obtained initial operational capability, GPS has rapidly become an integral component of the emerging global information infrastructure. Its applications range from mapping and surveying to international air traffic management, global change research, and precise timing for synchronization of financial institutions and cellular networks. The growing demand from military, civil, commercial, and scientific users has generated a US commercial GPS equipment and service industry that leads the world. In fact, GPS-related goods and services are expected to grow to an expected market size of US $757 billion by 2017.[1] However, challenges have arisen to GPS sustainment and growth. While the space segment gets most of the attention from the technology community and the user segment has millions of user-constituents, the control segment (CS) has been the province of a smaller body of experts and professionals.

Since its inception, the heart of the GPS CS was a 1970s-era mainframe computer system that had limited flexibility. Today the Architecture Evolution Plan (AEP) is becoming the key element of an overall modernization plan to improve operations, sustainment, and enhance world wide GPS service. AEP is a planned, phased delivery of a modernized command and control system for GPS Block II/IIA/IIR/IIR-M/IIF satellites. It delivers upgrades that ultimately provide GPS users with a more accurate and more useful positioning, navigation and timing (PNT) product. According to Lt Gen Michael A. Hamel, Space and Missile Systems Center commander and program executive officer for space, "AEP will usher in a new era of continuously improving mission performance and provide a foundation to incorporate new capabilities in the future."[2] Key aspects of AEP include:

- A transition from the CS mainframe architecture to a distributed computing environment
- An upgrade to a graphical user interface (GUI) for the satellite operator
- An improved Kalman filter
- A new security architecture
- A new master control station (NMCS) at Schriever AFB, Colorado and an alternate master control station (AMCS) at Vandenberg AFB, California
- An increase in GPS monitor station (MS) network assets
- An increase in ground antennas (GA) for contacting GPS satellites
- An improved capability to control new generations of GPS satellites.

How do these improvements add capability for GPS users?

Distributed computing is a method of computer processing in which different portions of an application run simultaneously on two or more networked computers. Several computers working different parts of the application can merge or blend results in a predetermined, phased sequence. Distributed computing provides processing flexibility and efficient options for architecture upgrades and technology updates. AEP operators can run applications simultaneously instead of handling each "in turn." Consequently, operators can address two or more anomalous situations at the same time thus reducing the time users are negatively impacted by anomalies. Additionally, AEP shortens the time between the operator's entry of a satellite command to the actual effect on the satellite.

GUI is a method of interacting with computers that enables the satellite operator to use a mouse to manipulate windows, icons, and menus. For almost two decades GUIs have long been the standard computer interface and stand in sharp contrast to command-line interfaces of the mainframe era. The advantages of GUIs include: making computer operations more intuitive and easier to learn and use; providing immediate, visual feedback about the effect of each action; and leveraging the powerful multitasking capabilities of modern operating systems. For the satellite operator, GUIs enable more efficient task accomplishment, thus reducing the time it takes to detect, identify, analyze, and resolve anomalies. Fewer, less cumbersome commands, performance monitoring tools, and other applications on the screen provide operators with better situational awareness and ultimately improves decision-making.

Most AEP enhancements trace back to 1995 when the GPS Joint Program Office formed the Tracking Network Team (TNT) to identify potential GPS performance improvements and tracking network operational efficiencies. The TNT included representation from all of the relevant DoD organizations. Based on the recommendation of the TNT, an effort known as the Accuracy Improvement Initiative established four major objectives:[3]

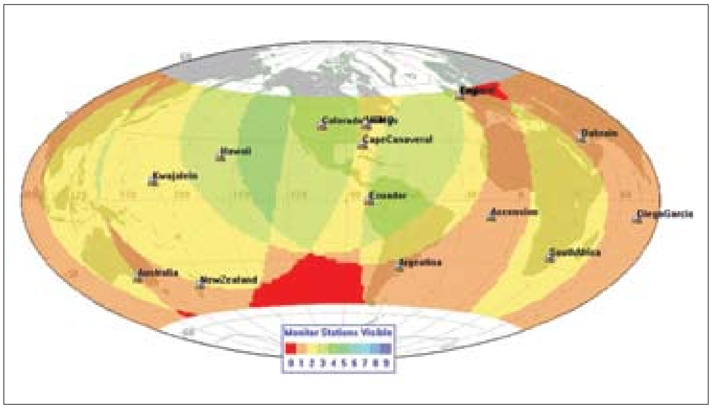


Figure 1. Coverage with Original Six Air Force Monitor Stations.

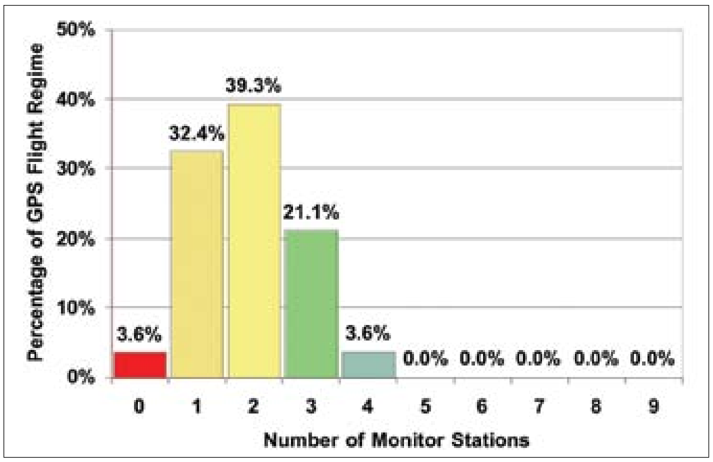


Figure 2. Coverage Distribution with Original Six Air Force Monitor Stations.

- Add data from the National Geospatial-Intelligence Agency (NGA) MS network to that available from the CS tracking network and use the additional data for L-Band monitoring and orbit prediction
- Transition the CS orbit determination/prediction process to use a single partition Kalman filter and incorporate improved geophysical and dynamic models
- Incorporate additional GAs for contacting GPS satellites
- Increase the navigation message upload frequency to three per day for each satellite.

AEP will provide the ability to implement the next generation security architecture known as selective availability/anti-spoofing module (SAASM) for authorized precise positioning service (PPS) users. SAASM adds physical tamper-proofing to user equipment and simplifies the security, handling, and distribution of cryptovariable keys. PPS users will have the ability to key their receivers using over-the-air-distribution and over-the-air-rekey procedures.

Formerly, the 1st Space Operations Squadron (SOPS) performed GPS launch and early orbit, major anomaly resolution, and disposal operations. The 2 SOPS performed routine day-to-day operations. Today, with the development of the Launch, Anomaly Resolution, and Disposal Operations system, the 2 SOPS and 19 SOPS perform these "cradle-to-grave" GPS operations in one facility known as the NMCS. Additionally, the development of a fully redundant and geographically separated AMCS to backup the NMCS ensures continuity of GPS operations.

From an historical perspective, the GPS constellation was operated with the original six Air Force MSs for more than 20 years even though those stations did not provide complete global coverage. Figure 1 projects the GPS original flight regime on a global map and clearly shows three unmonitored regions (red) with the largest unmonitored region occurring off the southwest coast of South America.

Figure 2 shows the distribution of coverage for the original MS configuration. Note that almost four percent of the GPS flight regime was completely unmonitored. Furthermore, almost a third of the flight regime was seen by only one MS at a time. This helps illustrate the fact that with only six MSs the loss of any one MS could substantially increase the portion of the unmonitored GPS flight regime.

The addition of NGA MSs has eliminated all unmonitored areas (figure 3). Figure 4 illustrates that all regions of single MS coverage have also been eliminated, and on average, GPS satellites are seen by more than four MSs.

The impact of these additional resources improves navigation uploads through better predictions as a result of the increased number of measurements provided to the Kalman filter.

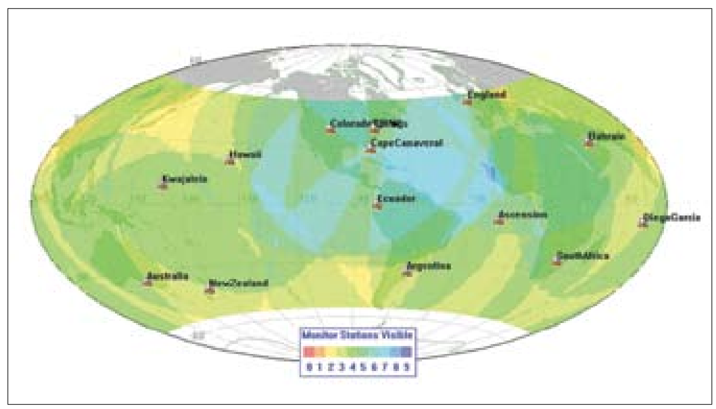


Figure 3. Coverage with Original Air Force Monitor Stations and National Geospatial-Intelligence Agency Stations.

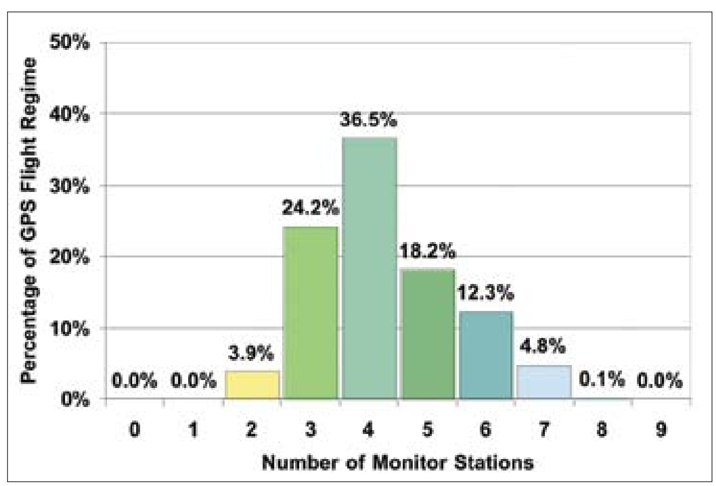


Figure 4. Coverage Distribution with Original Air Force Monitor Stations plus National Geospatial-Intelligence Agency Stations.

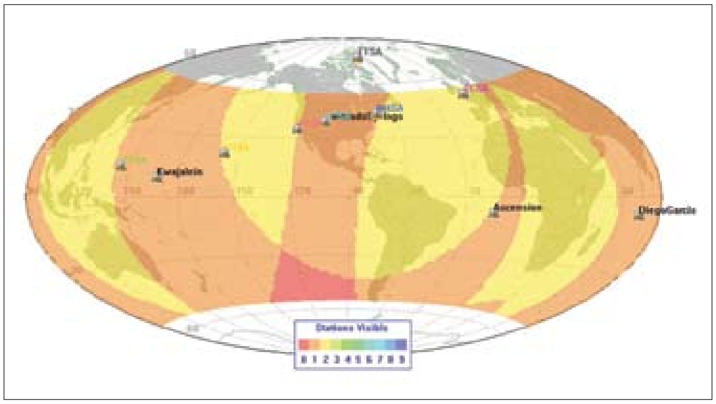


Figure 5. GPS Coverage with Ground Antennas Only.

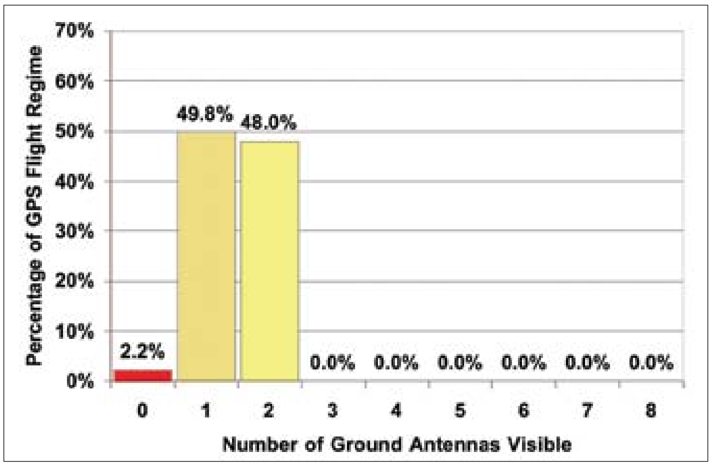


Figure 6. GPS Coverage Distribution with Ground Antennas Only.

This more accurate prediction of the GPS orbit benefits the user by decreasing the amount of error in position accuracy over time. The increased number of MSs decreases the time it takes operators to detect, identify, and correct anomalies.

For commanding GPS satellites, the CS originally had four GPS GAs located at Kwajalein, Cape Canaveral, Diego Garcia, and Ascension Island. The coverage provided by these original GAs is shown in figures 5 and 6. The addition of Air Force Satellite Control Network remote tracking stations through AEP tripled the number of available GAs as shown in figures 7 and 8. As a result, the average number of GAs visible to the GPS constellation has increased from under two to approximately four.

Even though AEP has made great strides in improving GPS capabilities, much work needs to be done to continue moving forward. AEP cannot put a navigation message onto, or fully control, the modernized signals such as the second civil signal or the dedicated military coded signal of GPS Block IIR-M and IIF satellites. Neither can AEP control the future GPS III satellites. Furthermore, the need for satellite operators and users to have an increased situational awareness of the GPS capabilities is outgrowing the capacity of AEP. The demands of the Global Information Grid and the call for flexible and expandable systems that can meet future needs without extensive redesign and operational disruptions require a satellite control system that takes advantage of modern enterprise architectures and new software development tools. Other drivers that mandate a new CS design include: a new focus on effects-based operations (PNT battlespace awareness); a focus on capability evolution (modern 'plug-n-play' approach); more automation to enable operators to implement capabilities to meet future operational needs; information assurance; and safety assurance. The continuation of AEP was considered but rejected because it lacks the robust infrastructure and architecture needed to support evolving GPS III capabilities and requirements. Based upon numerous studies, the best alternative to overcome system failures (integrity), preserve warfighter PNT advantages (anti-jam), increase position accuracy (zero/low-age-of-data), and

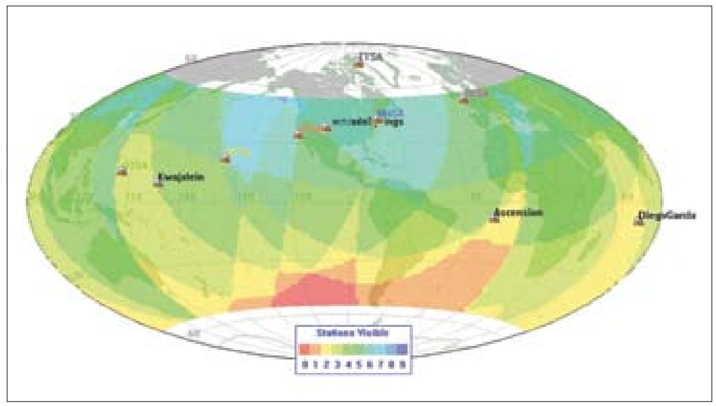


Figure 7. GPS Coverage with Ground Antennas and Remote Tracking Stations.

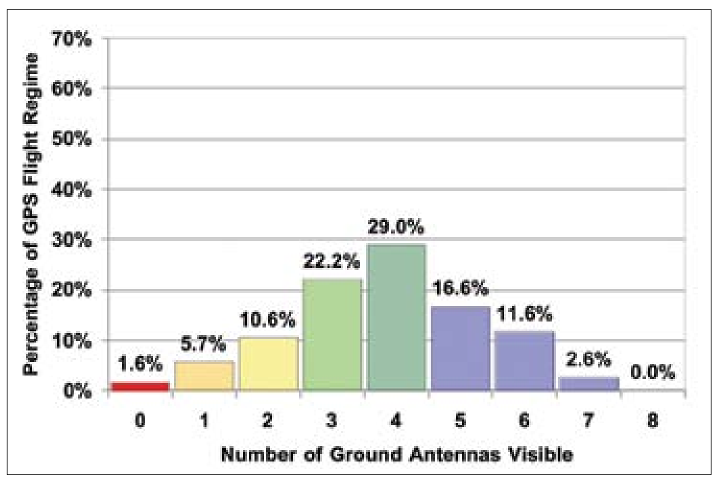


Figure 8. GPS Coverage Distribution with Ground Antennas and Remote Tracking Stations.

... the best alternative to overcome system failures, preserve warfighter PNT advantages, increase position accuracy, and facilitate near real-time command and control was to develop a new CS that has been designated the next generation control segment (OCX).

facilitate near real-time command and control (crosslinks) was to develop a new CS that has been designated thes.

OCX will provide command, control, and mission support for the GPS Block II and III satellites, as well as support to existing and new interfaces. OCX transforms the focus of GPS operations from satellite command and control to user-oriented, effects-based operations. Using OCX enables AFSPC to plan and control the constellation effectively so it can continue to provide full spectrum PNT information to all GPS users. As a replacement CS for GPS, OCX will incorporate net-centric operations (open architecture) technology that allows the system to evolve to meet growing GPS mission requirements. It will employ a modern, flexible, service-oriented (modular "plug-n-play") architecture that fully implements leading government and industry open systems standards.[4]

OCX will be a key step in achieving the Air Force space enterprise goal to establish common and compatible architectures, systems infrastructures, and open standards for all Air Force satellite command and control. The OCX approach will enable the Air Force satellite command and control systems to network solutions that can adapt rapidly to changing environments and significantly aid the incremental addition of new GPS capabilities in full support of GPS's "back-to-basics" block acquisition strategy. Proceeding along its own block acquisition strategy, OCX will be synchronized to support launch; telemetry, tracking, and commanding; on-orbit checkout; and operations of the first GPS IIIA satellites so it can deliver combat effects to the battlefield and business effects to the marketplace.

Notes:

[1] "Global Positioning Systems (GPS): The Road Ahead," RNCOS Report CICQ1149304, 1 May 2005.

[2] "Air Force Completes Transition of GPS Fleet to Upgraded Control System," Los Angeles AFB Press Release 010907, 17 September 2007.

[2] T. Creel, A. J. Dorsey, P. J. Mendicki, J. Little, R. G. Mach, B.A. Renfro, "Accuracy and Monitoring Improvements from the GPS Legacy Accuracy Improvement Initiative," proceedings of the ION NTM 2006, Monterey, California, 18-20 January 2006.

[4] "Air Force Space Command Capability Development Document for Global Positioning System III," 23 July 2007.

Additional References:

1. B. J. Stanton, R. Strother, "Analysis of GPS Monitor Station Outages," ION GNSS 2007, Fort Worth, Texas, 25-28 September 2007.
2. B. J. Stanton, "GPS Ground Station Gap Analysis," HQ AFSPC/A5NN, 12 September 2007.

Lt Col Harold W. Martin III (BS, Honors Mathematics, Purdue University; MS, Space Operations, Webster University) is the Positioning, Navigation, and Timing (PNT) command lead, Headquarters Air Force Space Command, Peterson AFB, Colorado. He is responsible for leading a matrix team across the command to synchronize issues across Global Positioning System (GPS) receivers, satellites, and ground systems; advocating PNT requirements for the command; developing budget investment strategy and enabling concepts; and represents the PNT capability area to sister services, US government, and international agencies.

Colonel Martin was commissioned as a distinguished military graduate from Air Force Officer Training School in 1988. His initial assignment was as the first Squadron Adjutant for the 71st Air Refueling Squadron at Barksdale AFB, Louisiana. He also became the squadron executive officer and deployed with the 2nd bomb Wing to Southwest Asia for operations Desert Shield and Desert Storm. Since then, he was the top graduate at Undergraduate Space Training and joined the 1st Space Operations Squadron, where he conducted launch and early orbit operations for one weather satellite launch and 12 GPS launches. He has worked on 14 different space systems to include navigation, weather, warning, communication, and intelligence satellites at levels from squadron through Air Staff and was the director of the Air Force Deputy Chief of Staff for Air and Space Operations Action Group. Prior to his current assignment, he was the operations officer for the 2nd Space Operations Squadron, where he oversaw all operations for the 32-satellite GPS constellation, the largest in the Department of Defense, and provided precise navigation information for over 43 major combat actions in Iraq and Afghanistan.

Colonel Martin is a graduate of Squadron Officer School, Air Command and Staff College and Air War College.

Mr. Walter "Pete" Petrofski (BA, Wilkes University; MSSM, University of Southern California; BA and MA, University of Colorado-Colorado Springs) is the GPS project lead for SI International, Incorporated in Colorado Springs, Colorado. He is responsible for supporting the command lead, Positioning, Navigation, and Timing Programs, Air Force Space Command (AFSPC) in the development of the GPS III and Military GPS user equipment capabilities documents. Mr. Petrofski retired from the Air Force in 1998 as a colonel after 26 years. He logged more than 2,500 hours in the B-52 before moving to AFSPC in 1987. He served as the director of operations, 1013th Combat Crew Training Squadron; team chief, AFSPC Inspector General; base commander, Thule AB, Greenland; and AFSPC competition advocate. He was the 1996 Air Force Competition Advocate of the Year and received the Legion of Merit. He is also a graduate of Squadron Officer School, Army Command and General Staff College, and Air War College.

GPS: Mission Success through Responsive Spacecraft Processing

Lt Col John Wagner
Commander, 45th Launch Support Squadron
Patrick AFB, Florida

Mr. George Houser
GPS IIR Launch Operations Site Manager
Lockheed Martin Space Systems Company
Patrick AFB, Florida

Mr. Don Skinner
GPS Manager, Eastern Range Directorate
The Aerospace Corporation
Patrick AFB, Florida

"The end for which a soldier is recruited, clothed, armed, and trained, the whole object of his sleeping, eating, drinking, and marching is simply that he should fight at the right place and the right time." ~ Carl von Clausewitz

The Global Positioning System's (GPS's) position, navigation, and timing signal is a keystone to the evolution of precision warfare and a large factor in the current revolution in military affairs. During the last two decades, our joint force methodology for finding, fixing, targeting, tracking, engaging, and assessing enemy targets along with nearly all joint force operations leading toward those ends have resulted in a smaller but more effective force. Resupply missions, for example, now occur at precisely the right place and time even in featureless terrain without fear of misreading maps or distance. This right place, right time mindset has also revolutionized worldwide industry, as GPS is the standard baselining billions of daily decisions in our global economy.

Responsive Spacecraft Processing

These are motivating factors toward total mission success. As we write this article, our combined government/contractor spacecraft team completed the processing and launch flow of the third remaining GPS IIR spacecraft. A Delta II carried this satellite—GPS IIR-19(M)—to orbit on 15 March 2008. IIR-19(M) is the sixth modernized GPS replenishment IIR(M) spacecraft, carrying the stronger military code and a second civil signal called L2C that provides 24 dB of increased protection against cross correlation and continuous wave interference, increasing the power for signal reception on smaller devices, and enabling dual frequency users to perform a number of new applications that include advances in agriculture and oil and mineral exploration. This spacecraft replaced GPS IIA-15 (launched 9 September 1992) in a 10,898 nautical mile orbit. It was the 47th GPS vehicle launched from Cape Canaveral Air Force Station (CCAFS) after arriving from the factory on 20 September 2007, undergoing initial inspections and then storage here at CCAFS while our team processed IIR-17(M) (launched 17 October 2007) and IIR-18(M) (launched 20 December 2007).

Upon removal from storage in early January, we put IIR-19(M), also known as SV08 or SVN48, through its paces in our defined IIR standard 60-day processing flow. We have been somewhat faster—the IIR-16(M) flow was 53 days, but the contracted "standard flow" activities occur at the right pace to ensure mission success while avoiding multiple shifts and a large workforce but still being in synch with the booster readiness schedule. Our major GPS processing flow steps include flight battery installation, a launch site performance test to checkout spacecraft electrical and mechanical systems, a compatibility test to ensure the vehicle can communicate with its ground station and control networks, installation of the solid-propellant apogee kick motor, an accurate spin balance and adjustment, spacecraft fueling followed by mate to the booster

Figure 1. GPS IIR(M)-20 Spacecraft Transport from the Lockheed Factory in Valley Forge, Pennsylvania, to Cape Canaveral Air Force Station.

Figure 2. GPS IIR-18(M) Spacecraft on the Spin Table in the LCSS Spacecraft Processing Facility.

upper stage, and transport from our processing facility to the launch complex. After mate to the Delta II booster, we perform satellite pad functional testing to verify no damage occurred to the GPS spacecraft during transport to the launch complex. Following payload fairing (PLF) installation, post-fairing satellite aliveness tests are performed to ensure no inadvertent damage occurred to the satellite during the PLF installation process. About the same time, our teams conduct final mechanical close outs, install PLF doors, and load final flight software on the spacecraft. These nominal activities are typically interspersed with fleet inspection and rework issues and framed by focused incremental readiness reviews chaired by the 45th Launch Support Squadron (45 LCSS) to ensure the spacecraft contractor, facilities contractor, and government agencies all are on the same page to press forward with acceptable technical risk to the next major phase of activity.

While much has been said regarding the need for "ship and shoot" spacecraft, the need to checkout, fuel, and integrate the spacecraft with the launch vehicle will remain. Vehicle inspection, mechanical and electrical testing, compatibility testing, fueling, integration and fairing encapsulation are all necessary steps for vehicles designed to operate continuously and autonomously for several years after they leave CCAFS's beaches. Fourteen GPS Block IIA spacecraft, for example, continue to outlive their original 7.5 year design life with an average age of 14.25 years, and a significant portion of the mission success credit goes to the work done at the launch base.

As spacecraft programs mature and encounter component, or "box-level" issues with vehicles in various stages of production or even on-orbit, unplanned but necessary checkout and rework is required at the launch site. Nearly 60 flight boxes were removed, reworked and replaced while processing 28 GPS IIA spacecraft for launch due to reach-back concerns, upgrades, and failures discovered during launch site testing. All of the rework was performed by a resident government and contractor team at the launch base, enabling quicker return to flight and minimal handling and therefore less risk than transporting the vehicle back to the factory for rework. Not one of the GPS IIA spacecraft returned to the factory for repair or systems-level space environmental retesting, and each of these vehicles performed well beyond design expectations on-orbit. The CCAFS team returned only three GPS IIR vehicles to the factory: one was a pathfinder and therefore intended to return, one for a mission data unit issue, and only one for major rework. The latter was only after extensive fuel purging over the course of a month here at the launch base. Originally intended to fly as IIR-3, GPS SV-10 returned to Valley Forge for rework and was selected for modernization after water leaked through several openings in the SLC-17A white room 8 May 1999. The SV-10 spacecraft will now be the last IIR mission, IIR-21(M), scheduled for launch in September 2008.

Successful spacecraft pre-launch processing requires a myriad of people and processes working together in specially designed facilities. The majority of processing requires a 'clean room' facility usually designed for 10 to 100,000 class clean or better, meaning less than 10 to 100,000 particles in a cubic foot of air, depending on the cleanliness requirement. This is considerably clean, as millions of dust, skin, and other particles are present in a normal standard cubic foot of air. In addition, some type of administrative facility to generate and review procedures and drawings must be available along with a control center for commanding and monitoring the many telemetry points on each of the spacecraft's subsystems during testing and launch. Other critical facility system support comes in the form of extensive and maintained voice, video, and data communication systems between the satellite, the satellite processing facilility, the launch complex, and the control segment which ultimately takes control of the satellite in space. Other critical satellite processing facility subsystems for GPS include a spin balance machine, a granite table for solar panel deploy-

ment, overhead cranes, fuel scrubber systems, radio frequency antenna systems and facility nitrogen–each of these systems and subsystems must be continuously maintained and ready for use. Uninterrupted, filtered technical electrical power is also required for the spacecraft test equipment located in processing areas. At CCAFS, we are migrating away from multiple aged facilities requiring continuous repair to an upgraded Spacecraft Center of Excellence not only for GPS, but one that all Department of Defense (DoD) payloads—small, medium, and large—can leverage for economies of scale within a secure area.

Mission Assurance and the Mission Success Partnership

All of the planned testing is outlined in a contractor provided document referred to as the launch base test plan. Specific work steps are written in processing procedures and carefully reviewed by contractor and government personnel prior to implementation. This effort reduces the probability of procedure related errors by eliminating obvious mistakes ahead of time and pre-coordinating the operation(s) before effecting flight hardware. When the approved procedural steps do not produce the desired result on flight hardware or an anomaly is discovered, the "root cause" must be properly isolated and identified. Improperly isolating and correcting these issues could very likely lead to, and has *led* to, mission degradation or failure.[1] The importance of mission assurance and an independent risk assessment provided by the government team is a critical factor in maintaining a solid track record of success for DoD spacecraft missions since the 1999 Broad Area Review. Some of the main items we look for are test-like-you-fly exceptions, critical qualification margins, first-flight items (of which we have many on new programs), single-point failures, nonconformance, test anomalies, escapes from testing, unverified failures, out-of-position/out-of-sequence work, and out-of-family results.[2] For GPS, government team members have always been imbedded in and responsible for launch base processing. This prevents a single individual from independently making critical trades or assessments without providing a rationale to the government customer. Mission failures do not just happen during launch or on orbit—many can be traced to a missed step or a misinterpretation of a poorly worded procedure during assembly in the factory or processing at the launch base. The GPS team continually conducts parallel contractor/government reviews and all members roll up their sleeves to tackle challenges as they arise, always with a critical eye on technical risk.

This teamwork was evident when it was discovered that one of 48 threaded captive fasteners required to install the apogee kick motor (AKM) to the spacecraft for the GPS IIR-16(M) mission was not threaded. An initial recommendation to fly with 47 of 48 bolts installed was discarded when further analysis revealed a faulty assumption. The AKM "swells" during firing, and the hoop stress created during this portion of flight could have created a localized shear producing off axis thrust and possibly mission failure. Rather than aborting the scheduled mission and returning the vehicle to the factory for rework, the launch base team designed, fabricated, and installed a unique pin bracket from approved flight hardware. The technical details of the pin bracket's form, fit, and function were coordinated and approved for flight, leading to launching on schedule with no increased risk to mission success.

Another example of integrated teamwork occurred during the IIR-18(M) mission. We encountered a problem while attempting to mate a safe and arm connector just prior to the transfer to the launch complex. Upon investigation, two of the four alignment keys should have been removed from the connector per a 10-year-old engineering change. A jumper harness was fabricated and installed after the spacecraft was mated to the booster, and analysis performed by both contractor and government teams independently confirmed a small balance weight was needed to counter the slightly off-axis jumper harness. The team worked together on the solution, yet performed indepen-

Figure 3. GPS IIR-18(M) Encapsulation at SLC-17.

dent technical analyses to validate the results while minimizing technical and schedule risk. Numerous other examples illustrate how proactive and positive teamwork between contractor and government personnel at the launch base leads to mission success. Each GPS block has been a superior spacecraft design, but the CCAFS team performed critical cross-checks ensuring all vehicles were ready for flight. This is done by a team with a minimal footprint—less than 90 people on the combined contractor/government team performing a launch rate (IIA) that peaked at nine launches in 15 months and now less than 50 people on the IIR combined launch base team processing one to three vehicles simultaneously. The GPS spacecraft processing team successfully processed and launched 28 II/IIA and 19 IIR spacecraft and all but IIR-1 (launch failure) performed successfully on-orbit.[3]

Organizing for Success: Back to the Future

The criticality and importance of an integrated spacecraft processing squadron is only just beginning to reappear. The nexus between space acquisition and space operations is here at the launch base, where various contractors assemble, test, and integrate thousands of components that comprise space and launch vehicles. During the past decade, we have come to define spacelift as consisting of launch vehicles, upper stages, launch complexes, and launch support facilities—all charged to get a booster to put a payload in a precise orbit. However, if the spacecraft does not deploy, communicate, and perform as designed, the flawless efforts by the booster and spacecraft factory and range teams consisting of hundreds of people and years of effort quickly become futile. Worse, a capability needed to support joint forces worldwide is not realized. Though not obvious by name alone, the 45 LCSS is charged with conducting mission assurance, technical surveillance, and risk assessment for DoD payloads launched from the Eastern Range, along with field management activities in direct support of Space and Missile Systems Center's spacecraft system wings and other DoD spacecraft system program offices. Activated in 2005, the 45 LCSS traces its heritage to the 6555th Aerospace Test Group's Space Vehicle (SV) Division from the 1970s to the early 1990s under Air Force Systems Command and the 45th Spacecraft Operations Squadron (45 SPOS) from 1991-1994 under Space Command. In "back to the future" irony, major issues facing the LCSS are the transition and last flight of heritage programs (DSP, GPS IIR) begun under SV and SPOS to the first flight of new programs with new contractor and program office teams (Space Test Program-1, Space Based Infrared System, Advanced EHF, Wideband Global SATCOM, Mobile User Objective System, GPS IIF, and others) while facilitating new starts and base support agreements for programs such as GPS III.

In summary, the integrated contractor/government team approach employed by the GPS program has become our first national model for responsive spacecraft processing and we are applying the successful GPS 'recipe' across the scope of spacecraft processing through the 45 LCSS. We have launched more GPS vehicles than any other in the Air Force or DoD, and the critical lesson from this program is understanding that sustained mission success depends on a good spacecraft design, but also hinges on the flexibility provided by the on-site contractor and government technical team here at the launch base. This expertise is critical to properly assess and overcome the varied challenges encountered while processing spacecraft for launch.

This approach demands that all team members fully participate in the process and be held accountable for their actions. The government team is held accountable through the mission assurance and risk assessment process and the government team holds the contractor team members accountable for their actions through contract oversight and periodic award fee cycles. Thus, the integrated contractor and government teams function as a complex interdependent force while solving problems, yet each take advantage of independent validation processes to maximize mission success. The teaming of both contractor personnel and government personnel at every level in the process provides the greatest synergy at the lowest cost due to participatory leadership with the accountability necessary to maximize success. The inclusion of both teams as mission partners provides a natural blend of knowledge, skills, and abilities capable of solving the most difficult problems both for assured access *to* space, and ensured spacecraft mission success once *in* space.

Notes:

1 Paul Cheng and Patrick Smith, "Learning from Other People's Mistakes," *Crosslink* 8, no 2 (Fall 2007): 20-24, US Government Satellite and Launch Vehicle Failures from 1990 to 2006, 22-23.

2 Tom Frietag and Bernardo Higuera, "The Role of Independent Assessments for Mission Readiness," *Crosslink* 8, no 2 (Fall 2007): 6-9.

3 Combined constellation operational average life to date is now over nine years. GPS IIA-11, launched on 3 July 1991, is the oldest GPS currently operational on-orbit, www.GPS-Today.com.

However, if the spacecraft does not deploy, communicate, and perform as designed, the flawless efforts by the booster and spacecraft factory and range teams consisting of hundreds of people and years of effort quickly become futile.

Lt Col John Wagner (BS, Astronautical Engineering, USAFA; MS Astronautical Engineering, AFIT; MBA University of Maryland-Europe; MMOAS, ACSC; MAAS, SAASS) is the commander of the 45th Launch Support Squadron (LCSS), Cape Canaveral AFS, Florida. The 45 LCSS is responsible for payload processing, launch vehicle integration, and critical infrastructure for Department of Defense spacecraft launched from the Eastern Range. Colonel Wagner was first assigned to Cape Canaveral AFS in 1991 as a Titan IV launch vehicle engineer responsible for Titan IV propulsion, mechanical systems, payload fairings, and payload integration for national security spacecraft.

In 1996, Colonel Wagner was assigned as a space-based missile warning flight commander at the Defense Support Program's European Ground Station. He later served as an operations evaluator and the commander of the Operations Support Flight, responsible for training, crew force management, operational procedures, and mission analysis.

In 2000, Colonel Wagner was assigned to the Space Warfare Center as the chief of advanced technology and later as the deputy chief of the Wargaming and Simulation Branch. In that capacity, he was the operations director for the first US space-centric wargame, Schriever 2001, and game director for Schriever II, the first coalition and interagency space wargame. Colonel Wagner later served as the speechwriter for the commander of AFSPC, authoring congressional testimony, posture statements, command priorities, and more than 200 national and international articles, briefings, and speeches.

From July 2006 to May 2007, Colonel Wagner was the operations officer of the 45th Launch Support Squadron at Cape Canaveral AFS. Colonel Wagner is a distinguished graduate of Undergraduate Space and Missile Training, Squadron Officer School, and Air Command and Staff College. He also graduated from the School of Advanced Air and Space Studies and Air War College (correspondence). He was a National Finalist for the White House Fellowship and received the Rotary National Award for Space Achievement in 2002. Colonel Wagner previously authored "Increasing the Solvency of Spacepower," published in Vol. 3, No. 1, of *High Frontier*.

Mr. George "Gordy" Houser (BS, University of Central Florida; BSME, UCF) has served as the launch operations site manager for Lockheed Martin at CCAFS where he has had the honor to lead a team of top notch satellite professionals to successfully process and launch 12 block IIR GPS satellites from launch complex 17. His launch team expects to fly out the GPS IIR program by mid September 2008.

Mr. Houser spent all but three years of his 28 year aerospace career at Cape Canaveral AFS (CCAFS), Florida. He started working as an airframe and powerplant mechanic with Eastern Airlines in Miami, DC-9s, B727s, L1011s, and A300s. Three years later, his first position at CCAFS was with Martin Marietta to work on the Titan 34D propulsion systems.

In 1988, Mr. Houser participated in assembling a brand new Titan IVB solid rocket motor upgrade team which successfully oversaw the construction of new facilities and upgrades to existing infrastructure (railroad tracks, launch frames, etc.) at CCAFS in addition to many successful launches it provided our nation "access to space". Mr Houser was involved in facility and Aerospace Ground Equipment modifications and engineering sustainment for the heritage Atlas programs (IIA, IIAS, III), as well as, Titan IV at CCAFS and vandenberg AFB, California. He has been a registered professional engineer with the state of Florida since 2002.

Mr. Houser was responsible for performance, cost and schedule to construct one of the three Atlas V major facilities that were erected on CCAFS (ASOC, LC-41, VIF). The Atlas Spaceflight Operations Center (ASOC) became his design showcase in that it took an existing structure (Motor Inert Storage – MIS) and transformed it more than 22 months to state-of-the-art horizontal EELV processing center and launch control center.

Mr. Don C Skinner Jr. (BS, Electrical Engineering, University of Central Florida) is the manager of the GPS Spacecraft Group within the Eastern Range Directorate of The Aerospace Corporation. Mr. Skinner began his aerospace career at the age of 19 as a summer hire with Rockwell International supporting the Space Shuttle program. He continued to support various functions within the quality organization in support of the first Shuttle mission while pursuing his engineering education part time.

In 1980 (seventeen months later) he became an electrical/mechanical quality engineer reviewing and approving real time Shuttle Orbiter engineering/procedure changes at the Orbiter Processing Facility, VAB and Pad 39A. Upon completion of his engineering studies, he transitioned to Lockheed as a space shuttle orbiter communication system engineer where he maintained test and launch responsibility for the Orbiter S-band PM, S-band FM, and UHF flight communication subsystems. He participated in 24 shuttle missions since first being hired as a summer intern. He joined the GPS program in December 1985 with Rockwell International as the TT&C engineer where he activated and tested the two dedicated ground test stations. He continued with the GPS program, joining The Aerospace Corporation in 1988 just prior to the delivery of the first GPS Spacecraft. Mr. Skinner has participated in 47 GPS missions processed and launched from Cape Canaveral. He has participated in the process as a working manager for the past 11 years.

The 2nd Space Operations Squadron Transforming Operations

Maj Michael A. Taraborelli
GPS Tactics and Mission Analysis Flight Commander,
2nd Space Operations Squadron
Schriever AFB, Colorado

It is nearly impossible to read an article about space power without seeing the three-letter designation "GPS" [Global Positioning System] and its revolutionary capability to provide combat capabilities to warfighters all around the world. It is also nearly impossible to open up your Sunday newspaper without reading an article about the latest GPS innovation or gadget on sale at the local electronics store. The fact of the matter is that GPS is integrated into the very fabric of our modern world. More than 1 billion people have come to rely on the precise timing and navigation signal that is as responsible for dropping weapons with precision as it is for guiding civilians safely through their daily journeys. There are countless ways in which GPS helps the world manage its daily affairs; this signal is so prevalent and reliable that it often is taken for granted. But what does it take to provide the most accurate positioning and timing signal in the world? Who makes it happen and what goes on behind the scenes? This article highlights the operational hub of GPS, the 2nd Space Operations Squadron (2 SOPS), 50th Space Wing, Schriever AFB, Colorado and its transformation during the last few years.

The 2nd Space Operations Squadron is a 150 member team of military and government civilians. In addition, there are approximately 100 Federally Funded Research and Development Centers (FFRDC) and commercial contractors providing direct world-class support to the 33 satellite constellation. The constellation itself consists of Boeing Block IIA and Lockheed Martin IIR and IIR-M (modernized) satellites orbiting the earth at approximately 10,900 nautical miles in six equi-distant planes inclined at approximately 55 degrees. The current constellation was designed to employ 24 satellites but the superb durability of the satellites coupled with the experience and the even more clever minds supporting the satellites realized a 33 percent increase in constellation capability by extending that capacity to 33 satellites.

The last few years were marked by unprecedented change in the squadron. At the forefront was the addition of an Air Force Reserve associate unit, 19 SOPS, which partnered with 2 SOPS (2/19 SOPS) to embark upon the most critical phase of GPS mission operations recorded to date—the transition to two new ground control systems: the Launch, Anomaly Resolution, and Disposal Operations (LADO) system in December 2007 and the $850 million Architecture Evolution Plan's (AEP's) Master Control Station (MCS) in September 2007. The accomplishment of these monumental tasks garnered *Aviation Week & Space Technology's* editor's choice as one of three most outstanding 2007 space achievements. The MCS is engineered on a distributed architecture system and allows telemetry, tracking, and commanding operations from the Air Force Satellite Control Network in addition to the five dedicated GPS ground antennas thereby more than doubling the contact capacity for updating GPS satellites with critical navigation and timing data. This was key since in 2007 GPS "flew" an unprecedented number of satellite sorties with the help of a phenomenal ground maintenance team which also ushered in the new LADO system.

The LADO system replaced the command and control system and the 1 SOPS GPS mission for launch, anomaly resolution, and disposal operations which are now under 2 SOPS satellite control purview. Key to the successful readiness and launch on the LADO system was support from 19 SOPS. The first LADO launch took place 17 October 2007 with the launch of SVN-56 and was a resounding success. Since then, three more modernized GPS Block IIR satellite launch missions have been successfully completed and the squadron is poised to launch the last two IIR-M satellites, SVN-49, and SVN-50, by the end of fiscal year 2008. While the squadron was busy with transitioning two internal ground control segments, it was equally as busy bringing new combat effects to the warfighter and additional capability for civilian users from the space segment.

Major Initiatives

In a recent *Joint Force's Quarterly* article, Air Force Space Command Commander, General C. Robert Kehler highlighted the importance of operating in three domains: air, space, and cyberspace while noting that: "Maintaining a future joint military advantage in an era of exponential change requires a more concerted effort to integrate these domains."[1] It is clear that change and technology are advancing at a faster rate than ever and becoming more important is the integration of these three domains. Over the last few years, 2 SOPS undertook an effort to transform itself as a squadron to keep pace with changes in the position, navigation, and timing landscape to integrate these three domains. While 2/19 SOPS accomplished a number of major initiatives, the following highlight the top three.

The first major initiative was the creation of a combined GPS user operations and weapons and tactics flight. The user operations section is a 24/7 operations center that interfaces with the military and civil GPS user communities providing support and information to users around the world. The flight provides more than 100 varying daily products such as satellite observation geometry, accuracy predictions, and interference analysis to allow warfighters and civil GPS users the best

possible support from space. In addition to planning products, the user operations section advanced integration of the three domains one step further with delivery of precise data to theater yielding an accuracy boost for equipped GPS users. The ability to quickly process information from the space and control segments, route through cyberspace and deliver to warfighters both on the ground and in the air was a monumental achievement for the squadron and for military operators the world over.

The second major initiative was the "Fly 32" team which reclaimed two pseudorandom noise (PRN) numbers that are also referred to as satellite identifiers, which had been used exclusively for test purposes, and grow the constellation size to 32 satellites realizing the full MCS constellation capacity of GPS. In particular, a combined 2 SOPS, 19 SOPS, GPS Wing, and contractor team successfully reclaimed PRNs 12 and 32 following a nearly 1.5 year intensive team effort by completing a series of technical interchanges, tests, and integrated weapon platform assessments. The team incrementally brought back PRN 32 from an unusable status and successfully set the record-breaking 31st GPS satellite 'healthy' for users on 26 February 2008. Incidentally, the satellite broadcasting PRN-32 is the oldest-ever, operational GPS satellite on record at 17.5 years. SVN-23, launched in November 1990, was once deemed "failed" due to extensive vehicle challenges but was brought back from a "mothballed" state through the combined efforts of operators, maintainers, vehicle contractors and FFRDC advisors. Again, the integration of a previously decommissioned space asset with the innovative technique of "double-booking" a PRN to allow for simultaneous operational and test use in the domain of cyberspace, granted two more mission-capable satellites for sea, air, and land users worldwide. One additional GPS satellite can make a difference between getting a degraded GPS signal and getting an accurate GPS-based location, whether it is for warfighters in Baghdad or firefighters in Boston. Both places have urban areas where a GPS user can only see a slice of the sky, an effect known as the "urban canyon," which means that they can not see all the GPS satellites that would normally be in view. This 31st satellite can not only help defeat the limitation of this urban canyon, it provides a five percent improvement in global constellation geometric performance.

The third major initiative was the Legacy Accuracy Improvement Initiative (LAII) where the initial 10 additional National Geospatial-Intelligence Agency (NGA) monitoring stations were added into the control segment. The addition of this data into the Kalman filter, which provides estimated satellite clock and ephemeris states necessary for keeping satellites updated, boosted signal integrity monitoring to more than 99 percent by three or more monitoring stations and boosted signal-in-space ranging accuracy by approximately 10 percent. LAII is incorporated in the AEP baseline and is providing increased mission robustness to the six operational control segment monitor stations.

Operation Constructs and Lessons Learned

At the heart of the success of the last few years of unprecedented change were the people. Lt Gen William L. Shelton noted in a previous *High Frontier Journal* article, "As we plan for the future, one thing is certain: space capabilities will be called upon at an increasing rate and it will be up to the men and women standing watch today to present a future that provides persistent, predictive space capabilities for the nation."[2] The men and women are at the heart of space systems and make possible the progress necessary for completing change and forging the GPS future. The following are three operating constructs and key lessons learned that have served 2 SOPS well during the last few years and will continue to serve as a model for the squadron in the years to come with respect to bringing new capabilities on-line.

Reserve Augmentation. The 19th Space Operations Squadron, the reserve associate unit to 2 SOPS, was key in the recent advancements of assuming two new ground control systems, a new mission, as well as providing daily operational support. There are a number of reserve personnel directly embedded within 2 SOPS which provide "corporate memory" and continuity to an ever-rotating active duty force. The combination of new experiences from rotating active duty members combined with the depth of corporate knowledge from the reserve unit provide a high degree of synergy for bringing new capabilities to the fight. One example involved the creative thinking of a reservist to transition a newly launched satellite from the LADO system to the AEP system two days earlier than accomplished on Legacy systems. This action was enabled by creatively using a new system to accomplish an analysis the Legacy system could not perform and resulted in the ability to bring a satellite into the prime ground control segment two days sooner. The reservist's in-depth system and mission knowledge combined with taking time to creatively think of a new way to do business yielded an operational improvement and standard for future satellite launches. By not only focusing on the process itself, but the inputs going into the process, a capability now exists for improved constellation management options!

Future Development. In his article, *The Elements of Successful Military Transformation: Applying Lessons Learned from Science, History, and Corporate America,* Dr. Michael Stumberg discussed the need for military organizations to transform and be adaptable to the ever-increasing rate of change in the world of information age warfare.[3] As the advance of technology accelerates and changes occur at a faster rate, the operational space squadron will find itself more involved in the development of new space systems. A paradigm shift took

One additional GPS satellite can make a difference between getting a degraded GPS signal and getting an accurate GPS-based location, whether it is for warfighters in Baghdad or firefighters in Boston.

place where the squadron became a bigger stakeholder in the acquisition process as well as increased interaction with end users. This paradigm shift is becoming more apparent as the combined 2/19 SOPS team is more of a "partner" rather than a "part" of the development of new satellites and systems with the acquisition community. The addition of the AEP and LADO control systems required operators to work "shoulder-to-shoulder" with developers in bringing on these two new systems. Operators bring a wealth of knowledge on the current system and are in the best position to make recommendations on how the system can operate better in the future. Even though the MCS is not yet one year old, design is well underway to the next-generation OCX ground control system. With the rate of change and technological advancement, operators will find themselves increasingly more involved with development. This same involvement with the ground control segment is also extending into the future GPS III satellite design and bringing to the table knowledge and experience gained from users worldwide through the user operations section.

Employing and Not Monitoring Your Weapon System. The user operations section has opened new lines of communication with military operators and civilian users all over the world, including a trusted user network (comprised of various agencies and organizations). From the farmer in North Dakota to the operator in Afghanistan, feedback from a myriad of users has helped reveal problems and brought new ideas to roll into future development as well current operations. The feedback from the user to the squadron operating GPS also allows the squadron to better serve the end user which in turn helps us to "employ" the GPS satellite system in a more useful way. A lot of the employment is found in the connection through the domain of cyberspace and how we are able to distribute a high number of daily products via the communications networks. Additionally, the information gained from the end user, when fed back to the acquisition community, can leverage resources to bring to bear capabilities once thought far off or even not yet conceived. The key is creating an open communication loop between the end user, operator, and acquisition community. It is becoming increasingly important for the squadron to find more innovative ways to meet the needs of the users. By solidifying lines of communication with other military and civilian users and development agencies, the 2/19 SOPS team continues to strive to find new ways to deliver GPS effects to the community.

Beyond the Horizon

As 2/19 SOPS looks forward to launching the next-generation IIF satellites and partnering in the development of the OCX ground control system and GPS III, there is still much work and innovation that continues within the squadron. While the MCS can control 32 satellites for GPS, 2/19 SOPS has set in place a plan to maintain additional satellites until the end of their serviceable life in LADO. The squadron continues to lean forward with increasing interaction between the end user and acquisition communities to collaboratively bring more capability to both military and civilian users utilizing readily available resources. By increasing communication within the GPS total system, 2 SOPS will continue to integrate and exploit the three domains of air, space, and cyberspace and give all users unprecedented capabilities in the future.

Conclusion

The GPS team consists of many: 2 SOPS, 19 SOPS, the GPS Wing, The Aerospace Corporation, Lockheed Martin, Boeing, and a number of other contractors and supporting agencies. The recent improvements of LAII, operating 33 satellites, and standing up a flight dedicated to breeding combat effects for warfighters in addition to superior service for civilian users is just the start. As 2/19 SOPS shifts its operations paradigm with increased development and user interaction, its success will solely rely on the efforts the military and civilian space professionals from the acquisition, operations, and sustainment communities. This paradigm drives itself to integrating the three domains to shape the future of the joint fight. The 2nd and 19th Space Operations Squadrons are dedicated to providing the best position, navigation, and timing signals to military and civil users and remains second to none!

Notes:

[1] General C. Robert Kehler, "Shaping the Joint Fight in Air, Space, and Cyberspace" *Joint Forces Quarterly* 49, 2nd Quarter, 2008.

[2] Maj Gen William Shelton, "Realizing the Unthinkable: AFSPC Influence Yesterday, Today, and Tomorrow," *High Frontier* 3, no 4 (August 2007): 18.

[3] Dr. Michael F. Stumborg, "The Elements of Successful Military Transformation: Applying Lessons Learned from Science, History, and Corporate America," *High Frontier* 3, no 4 (August 2007): 46-48.

Maj Michael A. Taraborelli (BS, Civil Engineering, U.S. Air Force Academy; M.B.A., Pepperdine University) is the GPS tactics and mission analysis flight commander for the 2nd Space Operations Squadron (2 SOPS), Schriever AFB, Colorado. He is responsible for GPS constellation maintenance and planning. His previous assignments include: student squadron commander, executive officer, flight commander, Officer Training School, Maxwell AFB, Alabama; chief, MILSTAR flight operations, executive officer, and Delta II second stage engineer, Los Angeles AFB, California.

Major Taraborelli is a resident graduate of Squadron Officer School and has completed Air Command and Staff College by correspondence.

Worldwide Influence of GPS and the Challenges Ahead

TSgt Teresa A. Medlock
Lead Specialist Missile Warning Support Element
21st Operations Support Squadron
Peterson AFB, Colorado

Not since the advent of the information age has any single aspect of technology had such a profound effect on the lives of people worldwide as Global Positioning System (GPS). Space-based position, navigation and timing (PNT) has moved into a close race with the internet by extending its impact and influence around the world during the last thirty years. Its initial concept focused on providing highly accurate, round-the-clock PNT in any type of weather.[1] During its early stages, it significantly improved military navigational capabilities in all types of operational environments. Since then, GPS and the PNT data that it provides have grown immensely. Its applications now impact military, governments, and civilians alike and it has proved to be an important part of the way the world conducts its business. All of this growth however, is not without challenges. The program and its managers face difficult issues with security and modernization every day. Finding and implementing solutions to these difficult problems presents program management with some of the most difficult technological, leadership, and strategic challenges that they have ever faced.

The use of GPS data has provided our military with great advantages since the program's inception. Its use in military operations, has virtually guaranteed continuous operational superiority in any sea, land, or air environment. At sea, GPS data helps to ensure safe passage of carrier battle groups through the Persian Gulf. On the battlefield, its use enhances combatant commander's capabilities to direct troop movements. In the air, it allows pilots to easily locate the enemy and ensure on target munitions delivery. All of these applications of GPS have had a great impact on operations that will continue to grow as new technology advances take hold.

The usability of this data in technological applications has also provided benefits to the civilian sector and has ultimately revolutionized the way in which governments and companies achieve their business objectives. Improved accuracy of location information has proved invaluable in surveying, transportation, and communications applications. Its use over cell phone networks can provide users with their location, download maps, and even guide them to their destination. It has the ability to locate the nearest police station or hospital, assist in locating a hotel, and provide travelers with notification of traffic problems ahead. Its safety applications are also quite impressive. It allows emergency services to identify the location of persons needing assistance, provides tracking systems for vehicles such as taxis, school busses, ambulances, and fire trucks, and can even track our children as they walk to and from school.

The contributions of space-based PNT are almost too many to count. With each passing day the list becomes even longer and each new capability brings a new set of challenges. The managers of the GPS program work to overcome these hurdles and ensure that the data provided is accurate, secure, reliable, and usable for the military and their civilian counterparts. Some of the most daunting challenges they face include improving the security of GPS data and the modernization of program elements.

The Security of GPS Data

Unfortunately, the world we live in can be a dangerous place making it necessary for all of us to be concerned with security in every aspect of our lives. Any type of data can be a target for those with other than honorable intentions. GPS is no exception. GPS signals use very low power making them vulnerable to various forms of interference.[2] The characteristics of this interference can appear in jamming or spoofing tactics to disrupt operations dependent on GPS data. Jamming is used to deny access to GPS signals and has been known in the past to cause real problems in both military and civilian sectors. Any crafty individual with internet access can easily find designs for a GPS jammer. Signals generated by this jammer could prevent GPS data from reaching users across an entire city or town. In-car navigation systems, vehicle tracking systems, timed communication systems, cell phone sites, and even aircraft receivers could all be affected. Spoofing on the other hand works quite differently; it generates signals that appear to be accurate GPS data when in fact they are not.[3] A spoofed signal could cause a receiver to produce incorrect or misleading information, inaccurate timing signals and positional information that could result in weapons or troops being led dangerously off course. These threats present very difficult challenges indeed. Thankfully, program managers and those on their team have had the foresight to develop and implement anti-spoof and anti-jam technologies and other security improvements into current system architectures. As successful as these efforts have been, we must continue to seek improvements in security technologies for all users program wide.

Modernization of Program Elements

In order to assure readiness for the future, GPS program managers must continually review current and imminent requirements. Four areas that are of particular note with regard to modernization are constellation design, satellite development, ground equipment maturity, and user equipment capabilities. Correct oversight of these areas will ensure that GPS can continue to keep pace with changing technology while providing users the reliability and usability they have come to rely on through the years. Modernization of any system can be a tedious process. In many cases getting satellite, constellation, or equipment changes developed, tested, and implemented in a timely manner can be very difficult under even the best conditions. Streamlining review and implementation processes while working in a degree of flexibility could

greatly accelerate these undertakings and make them much more economical.

Constellation design is a very important aspect of modernization. There are possible configurations that could be used with GPS, those with spares, and those without, each having its merits. Regardless of the configuration utilized, modernization and future constellation management will continue to be a costly and necessary endeavor. Program managers must ensure that the design of the constellation is flexible enough to be easily reconfigured in the event of a satellite failure as well as expandable to meet ever increasing user demand.

Development of new satellites is also a critical facet of the program. The upgrade to GPS III satellites is officially underway with the first of such satellites to launch sometime between now and 2013.[4] Once fully implemented, performance will be noticeably improved. GPS III will enhance current capabilities while also improving management efficiency. Some of the planned features include a new civil signal operating under an open service configuration, integrity monitoring of all signals, along with incorporation of a Distress Alerting Satellite System that would make it compatible with the COSPAS-SARSAT international search and rescue system.[5] This next generation of satellites will breathe new life into the program while extending its operation for years to come.

The ground equipment associated with GPS has been in operation for a number of decades and has served the program well by providing satellite command and control as well as monitoring of GPS data. There is one question however that every program manager, operator, engineer, and maintainer asks themselves from time to time. How can we ensure the operation of our equipment as it ages? Fortunately, the answer to this question has been answered for GPS. Plans for upgrading ground equipment are well underway and the changes will greatly enhance the systems operational capability and sustainability in the decades ahead. The recent transition of ground segment operations and completion of the fourth phase in the Architecture Evolution Plan went exceptionally well and was virtually seamless to the users of GPS data.[6] The new Operational Control Segment will provide full command and control of current and future series satellites.[7] Replacement of aging legacy mainframe computer equipment that can be upgraded as technology advances is also part of the modernization plan.[8] These improvements will likely ease the difficulties faced by operators and maintainers alike.

GPS success has set the stage for its own growth over time. This, in and of itself, presents its own challenges. In the earliest stages of the GPS program, developers must have questioned what the new navigational capability could do for the future and how they would get it to those that could use it. The question is still a viable one. As new technologies become available it seems that everyone wants to get on board with GPS. In this realm we do face a problem. The development of receivers usable in tactical environments takes time, and these units must be able to withstand the rigors of wartime environments. Plans are in the works to develop a new version of receiver for military use, but actually seeing them in the hands of the warfighter is likely a few years down the road.[9] Future integration of GPS enhancements into unmanned aerial vehicle aircraft, missile intercept capabilities, and robotics applications would also greatly contribute to our military's operational capacity and ensure continued superiority, but these changes take time as well. The need for the technology has now overtaken its availability and strides to improve this situation for those on the battlefield may likely be the program's biggest challenge.

Conclusion

In order to properly address these issues and continue to succeed, ultimately two things will be required; strong program leadership and continued funding. Given strong leadership that can streamline program operations, stand firm on requirements, and plan ahead to the future, money will continue to flow, and the program will continue to flourish. One thing is certain; GPS will continue to evolve in the years to come with its reach and versatility extending even further into our lives. Trying to predict just how far it will go would be impossible, but if the last thirty years have been any indication, it is a safe bet that its roles in the military and civilian sectors will be huge. The leadership of this important program has done well in getting us this far. There is little doubt that the GPS program will continue to easily weather the storm and come out ready to meet any challenges that lie ahead.

Notes:

1 Lt Col G. Tovrea and Dr. Aaron Pinker, "Contributions of the Global Positioning System", *Air and Space Journal*, Chronicles Online Journal Archives, 1995-1998, 4.

2 Eric Lagier, Desiree Craig, and Paul Benshoof, "JAMFEST—A Cost Effective Solution to GPS Vulnerability Testing," *Journal of Global Positioning Systems* 3, no 1-2 (2004): 40-44.

3 Steve Callagan and Hugo Fruehauf, "SAASM and Direct P(Y) Signal Acquisition," *Crosstalk*, Journal of Defense Software Engineering, June 2003.

4 Ray Swider, "GPS Status and GPS Modernization," briefing slides, 200, slide 10.

5 "GPS JPO Rethinks GPS III Strategy," Global View, *GPS World*, April 2005.

6 Don Jewell, "Leadership Talks, Back to Basics, Interview with Col Dave Madden," *GPS World*, October 2007, 31.

7 Ibid., 26.

8 Ibid.

9 Ibid., 30.

TSgt Teresa A. Medlock (BS, Information Technology and Computer Systems, American Intercontinental University) is currently assigned as lead specialist missile warning support element, 21st Operations Support Squadron, Peterson AFB, Colorado, where she provides operational support to 22 geographically separated units throughout AFSPC. She was previously assigned as instructor satellite wideband and telemetry systems, Detachment 1, 338th Training Squadron, Fort Gordon, Georgia, where she taught ground mobile forces SATCOM terminals, GPS, space systems, and telemetry equipment maintenance to pipeline students. While stationed at the 15th Communications Squadron, Hickam AFB, Hawaii, she served as a maintenance controller and satellite wideband and telemetry systems journeyman providing support to Joint Typhoon Warning Center storm tracking operations. She also served as a space systems journeyman at McClellan AFB, California, where she performed duties in support of depot operations by maintaining, repairing and refurbishing Defense Meteorological Satellite Program equipment and was involved in several initial operational test and evaluation efforts with various types of weather satellite tracking equipment.

Historical Perspective

Tracing Connections—Vanguard to NAVSPASUR to GPS: An Interview with Roger Lee Easton, Sr.

Dr. Rick W. Sturdevant
Deputy Command Historian
HQ AFSPC History Office
Peterson AFB, Colorado

The following interview by Dr. Rick W. Sturdevant with Mr. Roger L. Easton, Sr., occurred as a series of e-mail exchanges during December 2007, with an addendum in late March 2008. Throughout the last half of the 20th century, Easton contributed mightily to US Navy space activities from development of sounding rockets to design of the Vanguard satellite, and from development of the Naval Space Surveillance System (now the Air Force Space Surveillance System) to the design of experimental satellites for precise navigation and timing. His innovative leadership of the experimental Timation and Navigation Technology Satellite projects during the late 1960s and 1970s, resulted in technical achievements that became primary features of today's Global Positioning System (GPS). For his many pioneering achievements in spacecraft tracking, navigation and timing technology that led to GPS, Easton received the National Medal of Technology from President George W. Bush on 13 February 2006.

Interview

Sturdevant: Mr. Easton, you came to the Naval Research Laboratory (NRL) in Washington, DC, in 1943 as a physicist researching radar beacons and blind-landing systems for aircraft. When and how did you first become interested in, and involved with, space?

Easton: I transferred to the Rocket-Sonde Branch in 1952. There was an opening for which I applied, and I obtained the assignment. That branch was heavily involved in space, and so was I.

Sturdevant: Would you summarize your role in Project Vanguard, please, and describe the scientific purpose of the first Vanguard satellite?

Easton: My role in Project Vanguard was to supervise the construction of the first satellite and to work on the satellite tracking system called Minitrack, and to use it to find the position of certain islands in the Pacific. The location of these islands was in doubt because of the deflection of the local vertical. Secondary purposes of the satellite were to test the first solar cells in space and to provide two temperature measurements of the satellite.

Sturdevant: What were the major challenges in your invention of the Minitrack system for tracking the Vanguard satellite?

Easton: First, I did not invent Minitrack. It came from an X-band tracking system. Milt Rosen suggested we use a similar system at a much lower frequency. I looked at any problems such a change might entail. Essentially, there were none, and Minitrack was born. The only possible challenge was to provide a suitable transmitter in the satellite. We tried subminiature tube transmitters first. They worked marginally. Finally Bell Telephone/Western Union developed a very nice transistor for the task, and the problem was solved.

Figure 1. President Bush presented the National Medal of Technology to Roger Easton on 13 February 2006.

Sturdevant: Why was it necessary to develop the Naval Space Surveillance System (NAVSPASUR), and how did you improve the original NAVSPASUR fence?

Easton: NAVSPASUR was developed to preclude an enemy from flying a spy satellite over the US without our knowing about it. The system was improved continuously with the addition of receiving stations, with the addition of a large transmitter in the center of the line (Lake Kickapoo transmitter), with the addition of longer receiving antennas, and with

the changes in the receiving system to improve its sensitivity by about 24 decibels, a four-time increase in range. These changes enabled the system to detect objects at geostationary ranges. Another change was the addition of a second line, this one in southern Texas. This line was a true ranging-and-detection system—a RADAR. With it, objects crossing the US had orbits determined soon after the second fence was crossed. This information was most useful when a large number of pieces were present, as when satellites blew up or were blown up.

Sturdevant: In what basic ways did NAVSPASUR differ from Minitrack?

Easton: The main difference between Minitrack and the NAVSPASUR is that Minitrack used a signal transmitted from the rocket while NAVSPASUR used a signal reflected from the target. This difference had huge implications. For example, while the antennas for Minitrack were 50 feet long, those for NAVSPASUR were up to 100 times as long.

Sturdevant: How were your efforts to improve NAVSPASUR connected to your conception of using satellites for what has become known as precision navigation and timing?

Easton: We had a problem with synchronizing the transmitter to the receiver. We tried carrying cesium beam standards between the two sites, but the distance (about 100 miles) was such that the standards drifted between comparisons. Then came the idea: wouldn't this be an ideal place to use a satellite that would be visible to both transmitter and receiver simultaneously. Then

Figure 2. The NTS 2 or TIMATION 4 satellite developed by Roger Easton's NRL team was launched on 23 June 1977.

the satellite needs only a modulation to serve as a source of synchronization. And so a satellite, *Timation 1*, was built for this very purpose. However, before the satellite was built, the idea of using this technique for navigation came forth, and Timation [TIMe/navigATION] was born.

Sturdevant: What was your role in the development of the Timation satellites during the 1960s and 1970s?

Easton: I headed the Space Applications Branch from 1958 to 1980.

Sturdevant: How did those satellites evolve from *Timation 1* through *NTS-2*?

Easton: Both Timation satellites (1 and 2) used crystal oscillators as frequency sources, the main difference being that *Timation 2* had larger solar panels and a more powerful transmitter. At about this time Robert Kern and Arthur McCoubrey found a small rubidium oscillator being built in Germany. We hurried over to Switzerland and procured units for the *Timation 3*, also known as *NTS-1*, satellite. We had the units modified in time for launch, and they worked well for many months. For the *NTS-2* satellite, also known as *Timation 4*, Mr. Kern's company built two cesium units. These, unlike rubidium units, have the characteristic of being absolute frequency sources and, hence, were ideal sources for checking out Einstein's theory that clocks vary according to the gravitational fields they are in.

Sturdevant: How did you feel when you learned that the Air Force had been designated to lead a joint program office for development of a space-based navigation system to replace Transit? Were you personally involved in the transfer of Timation concepts and technology into the joint program when it began?

Easton: I was greatly disappointed, because the Navy had been the lead service in this program and allowed itself to be outbid by the Air Force. As to whether I was personally involved in the transfer of Timation concepts and technology, the answer is affirmative. We used all sorts of means to transmit our information to the joint program office (JPO). We even had one individual assigned permanently to the JPO to transfer information.

Sturdevant: What features of the GPS were derived in whole or part from Timation?

Easton: The entire concept of having a time-based system came from Timation—that's why it was named Timation for "TIMe navigATION." Timation was invented in 1964, and the first satellite was reported in *Aviation Week & Space Technology* on 27 November 1967. The earliest mention I have found in the same magazine for something like 621B is described in the 18 December 1967 issue. There, a concept for having an integrated communications-navigation-identification system was described. A four-satellite, Y-shaped constellation was described, with three or four such constellations required for global coverage.

Sturdevant: In what ways did GPS improve on Timation?

Easton: I can't think of any ways that GPS improved on Timation. Essentially, they are the same system. I might add that a proposal by Roy Anderson of General Electric to NASA had, essentially, the same constellation as GPS has, and it was proposed several years earlier.

Sturdevant: The Spring 2007 issue of *American Heritage of Invention & Technology Magazine* contained an article by Don Bedwell about the history of GPS development. Bedwell claimed that Col Bradford Parkinson, who had overseen the Air Force's 621B navigation satellite program before being assigned to head the GPS program office, believed the "side-tone ranging" signal used in Timation was more vulnerable to jamming than the system 621B spread-spectrum type of signal adopted for GPS. Would you like to comment on this assertion?

Figure 3. Roger Easton demonstrates Vanguard satellite to a curious youngster, ca. 1958.

Easton: The only cases of jamming of GPS that I know of were reported in *GPS World* some time ago. The source of this jamming was determined to be a local oscillator on a television set that fed directly into the GPS. I don't remember our Timation signals ever being jammed.

It might be instructive to look into why GPS jamming is so rare. The answer has to do with the environment the GPS receivers are in. GPS receivers are usually in places where people are scarce. The reason for this placement is that if many people are present, then someone or many know where he or they are. Of course, this statement is not always true. A person in congested traffic might not know where he is, especially with regard to the next turn he must make. But in most circumstances the navigator is alone in a boat or in an aircraft or on a hunting trip. So where is jamming a problem? On a battlefield it may be a problem, but even here the jammer may have a difficult task. If the jammer knows where the navigator is, he can overload the navigator's receiver with high-level signals, or noise, and make reception impossible. Another tactic that the jammer can use is to flood the field with cheap jammers as, for example, using a large number of microwave ovens modified to operate with their doors open.

What can the user do to mitigate the jamming signals? One thing he can do is use a directional antenna to pick up the navigation signal. It's a bit complicated, because he would need one directional antenna for each navigation satellite he intends to use. But, he could obtain perhaps 20 decibels less jamming with this technique. Jamming a user who is silent is not an easy task. Even jamming side tone ranging (STR) is not easy. The problem to the user is geometry and the square law. It's pretty difficult for him to jam the satellite transmission. With the satellite emissions off the table, the only thing left is to jam the received signals. And even that is not easy. That said, a study of PRF (pulse recurrence/repetition frequency) versus STR is called for.

Sturdevant: Were there aspects of Timation that the GPS program office chose not to pursue, but that might have made GPS better?

Easton: There are some changes that might improve GPS marginally. A higher inclination for the satellites will improve the high-latitude coverage. An eight-hour orbital period would improve the signal strength but only marginally. I might add that it appears to me GPS should have a program to get rid of its old satellites. The space world is getting cluttered.

Sturdevant: Undoubtedly, a number of individuals who worked with you or for you over the years helped advance your ideas and the resulting technology. Would you care to identify some of those people and their specific contributions?

Easton: One individual, Mr. Kern, helped by keeping the pressure on to use atomic frequency units. Not only did he keep the pressure on, but he and Mr. McCoubrey found the source in Germany, and they built the small cesium units that did such a nice job of confirming Einstein's predictions of the variation of clock frequency with gravitational fields. Then, there was the late Don Lynch, who calculated the Einstein effect and got it right on. Dr. Vince Folen was a reliable source for Einstein's theory. Al Bartholomew supervised the construction of the satellite that provided the information. James Buisson and Thomas McCaskill were vital in the field of finding the optimum constellation of satellites. I should not forget the support of the Naval Air Systems Command. Here I remember Capt David Crockett, Cdr David Heerwagen, John Job, and Chester Kleczek, all of the command. And, of course, there were many others.

Sturdevant: Chester Kleczek has said the Russians detected the range-measuring technique pioneered in *Timation 1* and based their Global Navigation Satellite System (GLONASS) on it. What do you think?

Easton: If the Russians have atomic frequency sources on all their satellites, and I believe they do, they are in all probability using the Timation technique. So, I agree with Mr. Kleczek.

Sturdevant: When you were experimenting with satellite navigation in the 1960s and 1970s, did you foresee the possibility of it becoming what many now call a "global utility"?

Easton: We foresaw a large population of users for the system, but we were careful not to over-emphasize the possibility as it might have been too much for the bean counters. It was one of those times that you walked a thin line.

Sturdevant: I noticed you still are working as an NRL contractor. Have you been working on space-related projects?

Easton: The answer is affirmative. During the latter part of 2007 and early 2008, the space-related project concerned the 50th anniversary of the launch of the first Vanguard satellite. We gathered information for the March 17th celebration. We found a film of the launch; then, we tried to find a better copy. We finally managed to get a film with audio attached, which was a triumph. Also, we had some good copies of the satellite, but we needed to determine which one we wanted to disassemble to show the internal construction.

Determining who is still alive among those who worked on the Vanguard project posed major challenges—so many have passed on that one must be careful to know who is still living. The most satisfactory triumph was to find that Milt Rosen, the project's technical director, is in pretty good shape and talked to two of my friends. They say he looked well.

Sturdevant: What part of celebrating the Vanguard satellite's fiftieth birthday was most meaningful, or memorable, for you?

Easton: Knowing that Milt Rosen is alive and well was extremely pleasant. Another high point was learning that a high school teacher attended and was thrilled. She gives her students a feeling for space.

Sturdevant: When it was launched fifty years ago, the Vanguard satellite's orbital lifetime was estimated to be 200 years, but that figure recently was extended to 2,000 years. How do you feel, knowing the satellite will have so many more birthdays in space?

Easton: It's nice to know that an old friend has many years ahead of it.

Sturdevant: What are you working on now that Vanguard's birthday party is over?

Easton: My current project is to set the record straight on the origins of GPS. I had one of the magazines straight and, then, the magazine was sold! Life is like that.

Readers seeking more information about Mr. Roger Easton and his space-related activities, particularly space-based navigation and timing, should consult the following sources:

1. Richard Easton, "Who Invented the Global Positioning System?" *The Space Review*, 22 May 2006, http://www.thespacereview.com/article/626/1.

2. Richard Easton, "Timation and the Invention of the Global Positioning System: 1964-1973," *Quest: The History of Spaceflight Quarterly* 14, 3 (August 2007):12-17.

3. Roger L. Easton, "Global Navigation Flies High," *Physics World* 20, 10 (October 2007): 34-38.

4. Constance McLaughlin Green and Milton Lomask, *Vanguard: A History* (Washington, DC: NASA, 1971), http://history.nasa.gov/sputnik/toc.html.

5. Thomas B. McCaskill, "GPS Inventor," http://www.gpsinventor.com/?page=home.

6. *The Review of Scientific Instruments*, February 1959 issue.

Dr. Rick W. Sturdevant (BA, History, University of Northern Iowa; MA, History, University of Northern Iowa; PhD, University of California, Santa Barbara) is deputy command historian, Headquarters Air Force Space Command (HQ AFSPC), Peterson AFB, Colorado. He joined the Air Force History and Museums Program in April 1984 as chief historian, Airlift Information Systems Division, Scott AFB, Illinois, and moved one year later to the Chidlaw Building near downtown Colorado Springs as chief historian, Space Communications Division (SPCD). When SPCD was inactivated in 1991, he moved to the HQ AFSPC history office and became deputy command historian in 1999.

An acknowledged expert in the field of military space history, Dr. Sturdevant appears frequently as a guest lecturer on space history topics and is author or co-author of chapters or essays in *Beyond the Ionosphere: Fifty Years of Satellite Communication* (1997); *Organizing for the Use of Space: Historical Perspectives on a Persistent Issue* (1995); *Golden Legacy, Boundless Future: Essays on the United States Air Force and the Rise of Aerospace Power* (2000); *Air Warfare: An International Encyclopedia* (2002); *To Reach the High Frontier: A History of US Launch Vehicles* (2002); *The Limitless Sky: Air Force Science and Technology Contributions to the Nation* (2004); and *Encyclopedia of 20th-Century Technology* (2005). His articles or book reviews have appeared in such journals as *Space Times*, *Journal of the British Interplanetary Society*, *Air & Space/Smithsonian*, *Quest: The History of Spaceflight Quarterly*, *Air Power History*, *High Frontier: The Journal for Space & Missile Professionals*, and *Journal of the West*. He sits on the editorial board of *Quest* and on the staff of *High Frontier*.

Dr. Sturdevant is an active member of the American Institute of Aeronautics and Astronautics (AIAA), American Astronautical Society (AAS), British Interplanetary Society (BIS), and Society for the History of Technology (SHOT). His professional honors include the Air Force Exemplary Civilian Service Award (1995-1999) and the AAS President's Recognition Award (2005).

Prepared Statement by General C. Robert Kehler

General C. Robert Kehler
Commander, Air Force Space Command

Before the
Senate Armed Services Committee
Strategic Forces Subcommittee
United States Senate
4 March 2008

Introduction

Mister Chairman. Senator Sessions and distinguished members of the subcommittee, it is an honor to appear before you today as an Airman and, for the first time, as the commander of Air Force Space Command (AFSPC).

I am proud and humble to lead and represent over 39,000 active duty, Guard, and Reserve Airmen; government civilians; and contractors who deliver space and missile capabilities to America and its warfighting commands 24 hours a day, 7 days a week, 365 days a year. We do this as an integral part of the United States Air Force (USAF)—an Air Force which operates in and through air, space, and cyberspace in order to deliver Global Vigilance, Global Reach, and Global Power for America. Assuring the Nation's access to space, protecting our freedom to operate in space, and providing joint warfighting capabilities from space are core Air Force missions.

The men and women of AFSPC serve around the globe. From AFSPC Headquarters, Fourteenth Air Force (14 AF), Twentieth Air Force (20 AF), Space and Missile Systems Center (SMC), Space Innovation and Development Center (SIDC), and a host of deployed and forward locations, our space professionals are organizing, training, equipping, and providing the space capabilities needed to fight and win the Global War on Terror. Today, I can report confidently that the space and missile capabilities acquired with your help and support and delivered by the Airmen of AFSPC to the commander, United States Strategic Command (USSTRATCOM) are helping to maintain America's freedom, security, and prosperity.

Last month, I visited a number of units and commanders in the United States Central Command (USCENTCOM) area of responsibility (AOR). At one stop I received a mission briefing from a B-1B Lancer bomber pilot. He reflected that while preparing for the briefing, he came to realize that space capabilities were embedded throughout the planning, execution, and debriefing phases of his mission. His bomber crew planned their missions using intelligence, surveillance, and reconnaissance (ISR) terrain mapping and weather data from space systems; the aircraft carried Global Positioning System (GPS)-aided Joint Direct Attack Munitions (JDAMs); when they were flying, real-time updates from a variety of space-based and other sources flowed to them over satellite communications (SATCOM) data links; the tanker and bomber crews coordinated air-refueling operations using GPS; and strike assessment was conducted. This pilot also knew that a combination of space, air, and terrestrial assets would immediately come to his assistance if his crew came down in hostile territory. In effect, space assets would take the search out of search and rescue. In the AOR, I saw firsthand how space plays a crucial role in virtually every mission and every operation. Every commander I visited confirmed this assessment.

Space power gives America's joint forces a decisive advantage and has shaped the "American way of warfare." Today, America's joint forces are interconnected, have global cognizance, and can produce swift and precise effects providing overwhelming and decisive results with minimum collateral damage. Our friends and adversaries alike have noted this decisive advantage. As a result, having witnessed or learned the cost of challenging the United States head-on, would-be adversaries are actively pursuing asymmetric strategies to challenge our advantages in air, space, and cyberspace. The evidence is clear and convincing.

During Operation Iraqi Freedom, we experienced GPS jamming and since then we have witnessed a worldwide proliferation of technology that can be used against our space systems. Our space capabilities face a wide range of threats including radio frequency jamming, laser blinding, and anti-satellite systems. The emergence of these threats requires a broad range of capabilities, from diplomatic to military, to protect our interest in space.

Our National Space Policy acknowledges that space is vital to our national security. We are not alone in our use of space. Today, 28 foreign militaries operate in space.

We can no longer take freedom of action in any of our warfighting domains for granted. From this point forward, we should expect to be challenged not only in the air, but in and through space and cyberspace as well. We clearly recognize that no future conflict will be won without the ability to achieve air, space, and cyberspace superiority when and where required, and we face significant challenges as we look to the future. Therefore, it is crucial that we develop and resource a strategy that protects our space advantages and ensures we remain a world leader in space.

It is my distinct pleasure to define the strategic way forward for AFSPC and to describe for you our plan to conceive, acquire, employ, and execute Air Force space and missile capabilities in an increasingly complex, dynamic, and challenging global environment. I will present our mission and vision, affirm the guiding principles that characterize our approach, highlight some of our recent successes, and describe how the fiscal year 2009 (FY 2009) budget request supports our strategic way ahead.

As always, AFSPC undertakes our important mission with three USAF priorities in mind—win today's fight, take care of our people and prepare for tomorrow's challenges. We look forward to working with your committee and the Congress to achieve our goals.

Mission

Deliver space and missile capabilities to America and its warfighting commands

Our mission is clear. For over 50 years, the Air Force has led the Nation's military space efforts, and AFSPC continues that heritage as we deliver space power to USSTRATCOM, joint force commanders around the globe, the services, the intelligence community (IC), civil agencies, commercial entities, and allies.

Vision

America's space leaders … delivering responsive, assured, decisive space power

The USAF provides air, space, and cyberspace power as part of a joint warfighting team. As we look to the future, the military space power element must become more responsive to the warfighter, it must remain assured under stressing conditions, it must contribute decisively as an integral piece of the larger whole, and it must be developed and wielded by space professionals who are recognized leaders in both the space domain and in joint warfighting operations.

Guiding Principles

The following principles shape our approach and underpin our mission and vision:

- *The USAF space mission serves joint forces, our Nation and the world at large.* The Nation has entrusted the Air Force and AFSPC with advocating, acquiring, and operating capabilities that are vital to our National security, economic growth, public safety, and welfare. The men and women of AFSPC help defend our homeland and our global interests abroad with space and ground-based missile early warning systems; connect national leaders and the military with secure global satellite communications; assure access to space for military, intelligence, civil, and commercial purposes with medium and heavy space lift and range capabilities; keep watch over the space domain by tracking thousands of space objects; provide planners and commanders with critical environmental information; and deliver persistent position, navigation, and timing (PNT) signals to worldwide users from GPS, which provides multiple military benefits as well as a free, international utility. Many of these space systems are also called upon for help in disaster relief and search and rescue operations, at home and abroad. Additionally, our Nation places trust and confidence in AFSPC to secure, maintain, operate, and support America's land-based strategic deterrent, the intercontinental ballistic missile (ICBM) force.
- *Nuclear forces underwrite our Nation's security.* Nuclear deterrence remains the ultimate backstop of our security by dissuading our opponents and assuring our allies through extended deterrence. Our Nation's security relies heavily on the responsive and stabilizing attributes of AFSPC's ICBM force.
- *Space is one of three interdependent USAF warfighting domains.* Air Force operations extend across the mutually supporting and reciprocally-enabling domains of air, space, and cyberspace. Thus, Airmen who are experts in the space domain play a key role in integrating capabilities to create a decisive joint military advantage. Cross-domain integration is the key.
- *Space and ICBM forces are global in their effect.* AFSPC delivers capabilities that transcend national and military boundaries and are intrinsically and simultaneously tactical and strategic, local and global. As a result, the men and women of AFSPC have a global perspective that influences the command and control of our forces and the way we provide and present them to USSTRATCOM. At the same time, we recognize the unique space requirements of US geographic combatant commanders around the world, and know that we must provide joint force commanders with the space capabilities they need to see, know, and decisively act.
- *Like air power, space power shapes the US approach to warfare.* Our increasingly net-centric, joint expeditionary force operates with smaller forward footprints and a greater dependence on reachback organizations. Space capabilities are inextricably embedded in an ever-more-effective arsenal of modern weaponry and are threaded throughout the fabric of the joint warfighting network. Without space, military operations would be far less precise, focused, timely, coordinated, or efficient as well as much more costly in every respect.
- *Space is a challenging, demanding, and contested domain.* Space acquirers, developers, and operators must be technically astute and tactically competent to ensure mission success in the space domain. While necessary, technical competence alone is not sufficient to meet 21st century challenges. Today, AFSPC people must be adequately prepared to operate space assets and assure space capabilities in an increasingly contested environment.
- *Airmen are the core of America's space team.* The Airmen and civilian space professionals of AFSPC serve a National mission and our skills and expertise are National assets. Since the beginning of the space age, Airmen have contributed significantly to the National space enterprise. While Airmen are serving the military space mission today in AFSPC, many other Airmen are working elsewhere in the government within national security and civil space organizations. Commercial space companies and the space industry also abound with space professionals who gained training and experience while serving our Air Force.

While these principles shape our views, our sights are set directly on supporting the Air Force commitment to provide forces across the range of military operations to protect US interests and values; to assure allies; to dissuade and deter potential adversaries; and if deterrence fails, to defeat those who choose to become our enemies. In answering this call, with Congressional support, the space professionals of AFSPC last year delivered space and missile capabilities with great success.

A Year of Successes

AFSPC activities in 2007 supported the Expeditionary Air Force, delivered and demonstrated space and missile capabilities, improved relationships across the space enterprise, and cared for our Airmen and their families. We are also optimistic that we have made progress toward solving our systemic acquisition problems with our back-to-basics approach. Here are several of our key accomplishments:

- We forward-deployed nearly 4,000 Airmen—further developing a strong bond between AFSPC and the Airmen, Soldiers, Sailors, and Marines who rely on our capabilities.
- The end of 2007 marked five consecutive years without premature failure of any AFSPC on-orbit system—many of our satellites are lasting years beyond their original predicted life spans and are exceeding expectations every day.
- AFSPC added to our all-time record which now stands at 56 successful National security payload launches in a row; we continued a string of excellence with 19 out of 19 successful operational launches using the Atlas V and Delta IV evolved

expendable launch vehicles (EELVs).

- In November, AFSPC conducted the first operational launch of a Delta IV Heavy EELV, which carried the last Defense Support Program (DSP) satellite into orbit.
- Without interruption of services, AFSPC completed the transition of the GPS ground control segment to the new Architecture Evolution Plan (AEP) system—replacing a 20-year-old command and control (C2) architecture with one that enables responsive PNT services.
- Last year, AFSPC launched Glory Trip-193 to certify the use of the Mk 21 safety enhanced reentry vehicle (SERV) on the Minuteman III (MM III) ICBM. Additionally, this test demonstrated the capability of our ICBM force.
- AFSPC and the National Reconnaissance Office (NRO) further solidified our operational relationship.
- In addition, AFSPC sustained and expanded use of the Total Force. Last year, at Minot Air Force Base, North Dakota, we stood-up the first-ever Air National Guard unit to support intercontinental ballistic missile field security forces. At Schriever Air Force Base, the AFSPC Reserve Forces are growing with the transition of the 310th Space Group to wing status.
- We privatized nearly 2,500 military family housing residences at Peterson, Schriever, Los Angeles, and Vandenberg Air Force Bases. Additionally, 351 AFSPC families moved into newly privatized units at Buckley Air Force Base.
- Finally, AFSPC experienced one of the safest years in its 25-year history—we lost no Airmen in off-duty accidents. Moreover, AFSPC has had zero major weapons mishaps in over four years, zero major flight mishaps in eight years, and zero major space mishaps in over two years.

As proud as we are of our successes, AFSPC's strategic way forward is to focus on delivering the space and missile capabilities needed today and tomorrow by balancing recapitalization and modernization investments, implementing organizational and cultural changes, and maturing our space professionals.

The Way Ahead

To defend America and provide needed capabilities to the joint team, AFSPC solidified over the last year a deliberate approach to confront the challenges of a dynamic strategic environment. The FY 2009 budget request carefully balances a number of critical priorities.

Priorities

Maintain perfection as the standard for nuclear operations, maintenance, security, and support

In AFSPC, we are absolutely committed to providing a credible, safe, and secure strategic deterrent. At any given moment, about 1,200 of the nearly 10,000 Airmen in 20 AF are on duty in the Nation's MM III ICBM missile fields in Montana, North Dakota, Wyoming, Nebraska, and Colorado. These young professionals understand the awesome responsibilities entrusted to them and will never take those responsibilities or the Nation's trust and confidence for granted. This year we will continue to sustain the Minuteman ICBM system as we selectively improve security measures and implement any necessary recommendations resulting from various nuclear reviews.

- *Standards.* We have defined perfection for ourselves through tough standards—which have been tested and proven for five decades. We follow these standards to the letter and focus on structured, intensive training for our maintenance, security, and operations personnel.
- *Minuteman Life Extension.* The FY 2009 budget request continues the Congressionally approved $6.7 billion life-extension programs that will sustain the MM III to 2020 as we work to identify further investments that may be required to sustain the MM III force to 2030. In January 2008, we completed deployment of the Guidance Replacement Program (GRP), which replaced some of the 1960s-generation electronics in the guidance system. Currently the Propulsion Replacement Program (PRP), which replaces aging motors and propellant as well as environmentally unsafe materials and components, is 82 percent complete. The remaining MM III modification programs (the SERV and the Propulsion System Rocket Engine Life Extension Program [PSRE LEP] upgrade) are still on target for completion by 2012 and 2013, respectively. The SERV program enables the use of the Mk 21 reentry vehicle on MM III missiles, providing USSTRATCOM planners with increased targeting flexibility and enhanced safety. The PSRE LEP is extending the design life of this subsystem by replacing components originally produced in the 1970s.
- *Security Modernization.* AFSPC is also continuing to field robust capabilities funded under the ICBM Security Modernization Program (ISMP). Last year, we completed the installation of concrete headwork barriers at all operational launch facilities (LFs) to ensure the safety and security of our nuclear arsenal. In 2008, we are continuing to improve real-time situational awareness for our security forces through the Remote Visual Assessment (RVA) program. AFSPC is also replacing LF access doors with ones that enable our personnel to more quickly secure the silo hatch in case of a security threat during maintenance operations. In addition, we are increasing the physical protection of our LFs with better technology and more effective tactics. AFSPC is also taking steps within our budget this year to add security surveillance cameras at our missile alert facilities (MAFs) and to add GPS tracking capability to payload transporter (PT) vans.
- *Prompt Global Strike (PGS).* Looking to the future, the FY 2009 budget request responds to USSTRATCOM's PGS needs by developing and demonstrating critical concepts and technologies for a conventional strike alternative. To increase our deterrence and conventional strike capabilities, AFSPC is investing in research and development of technology for guidance, reentry vehicle, and propulsion systems with the ICBM Demonstration/Validation (ICBM DEM/VAL) program, and is aligning these initiatives with the results of the recently completed PGS Analysis of Alternatives and with the Congressionally directed DoD-wide investment account.

Ensure mission success while delivering planned capability improvements

Joint force commanders and the forces they lead rely on the capabilities provided by AFSPC, and our operational commitment to deliver those capabilities to them every day can not falter. In addition to this operational commitment, we must also meet our

aggressive program commitments to field and sustain leading-edge space capabilities on time and on cost. AFSPC is on final approach to deliver several major new Military SATCOM (MILSATCOM); PNT; and ISR capabilities over the next 18 to 24 months.

- *MILSATCOM.* The demand for satellite communications and bandwidth continues to grow. Aged in many cases beyond their design, Milstar and Defense Satellite Communications System-III (DSCS-III) continue to provide critical communications services for much of the Nation's daily secure and unsecure military and diplomatic activities as we deploy the next generation of advanced MILSATCOM capabilities.
  - The Wideband Global SATCOM (WGS) program provides communications capabilities greater than the entire constellation of DSCS-III satellites and increases coverage, capacity, and connectivity for deployed tactical forces. In 2007, AFSPC launched WGS-1 and the Air Force negotiated a partnership with Australia to use the constellation and fund the procurement of a sixth WGS satellite. The FY 2009 budget request funds continued operation of WGS-1, on-orbit checkout and operation of WGS-2, and launch technical support and on-orbit checkout of WGS-3. WGS-4 and WGS-5 are currently in fabrication.
  - Our Advanced Extremely High Frequency (AEHF) program affords strategic and tactical users with secure, survivable anti-jamming and antiscintillation communications. Each AEHF satellite has about 10 times the capacity of Milstar II. The FY 2009 budget request supports the launch and on-orbit checkout of AEHF-1; completion of integration and testing of AEHF-2 for launch in 2009; continued assembly, integration, and testing of AEHF-3; contracting of AEHF-4; and work on the Mission Control Segment.
- *Position, Navigation, and Timing (PNT).* AFSPC is delivering PNT capabilities which are providing critical military benefits as well as a free international utility. Our GPS is the centerpiece of global PNT services, and the GPS constellation enables an ever-increasing arsenal of precise munitions from the mainstay JDAM to the Air Force's new, small-diameter bomb (SDB) and from the Army's Guided Multiple Launch Rocket System (GMLRS) to its Excalibur 155mm artillery round. Airmen in C-130 and C-17 aircraft are resupplying ground combat units in nearly, impossible-to-reach places in Afghanistan by using the remarkable Joint Precision Air Drop Systems (JPADS), which have steerable parachutes with GPS guidance.
  - Last year, AFSPC launched two modernized GPS IIR-M satellites configured with new signals for increased anti-spoofing and anti-jamming capabilities for military users and more robust capabilities for civil users. With five of eight GPS IIR-M satellites on-orbit, AFSPC is launching the remaining three in 2008.
  - The follow-on block is GPS IIF which will have an extended design life of 11 years, include additional civil signals for improved accuracy and safety-of-life services, and increased power to reduce vulnerability to signal jamming. The ground segment includes a master control station and a worldwide network of dedicated antennas and monitoring stations. The FY 2009 budget request supports launch and support of two GPS IIF satellites and delivery of the final architecture evolution plan.
  - In concert with upgrades in the GPS space segment, we are also improving the GPS ground segment. AFSPC launched the last two GPS IIR-Ms using the new Launch, Anomaly Resolution, and Disposal Operations (LADO) system; replacing an obsolete command and control system with a more modern and sustainable one.
- *Intelligence, Surveillance, and Reconnaissance (ISR).* Our Nation has relied on Air Force space-based missile warning systems since the early 1970s.
  - AFSPC's Defense Support Program (DSP) provides missile warning, missile defense, battlespace awareness, and technical intelligence collection capabilities.
  - The Spaced Based Infrared System (SBIRS) program provides missile warning, missile defense, intelligence, and battlespace awareness capabilities and will replace DSP. The SBIRS constellation will consist of four geosynchronous Earth orbit (GEO) satellites and two highly elliptical orbit (HEO) payloads.
  - The first on-orbit SBIRS-HEO payload continues to exceed expectations in its checkout phase resulting in approval for early use in December 2007 and is on track to reach full operational acceptance in mid-2008. Additionally, HEO-2 has been built. On SBIRS GEO-1, AFSPC is correcting a safety issue in the flight software and is planning a launch in 2009. The FY 2009 budget request for SBIRS funds development, integration, and test of GEO-1 and GEO-2 satellites and ground systems; funds initial HEO operations; fully funds HEO-3 and GEO-3 procurement; funds HEO-4 advanced procurement; and funds HEO ground system modifications and upgrades. The HEO-3 and HEO-4 payloads are designated as constellation replenishment assets.
- *Launch, Ranges, and Networks.* Delivery of space capabilities begins with a successful launch. Our two space launch ranges at Patrick and Vandenberg Air Force Bases continue to be the lynchpin for America's assured access to space.
  - At our Eastern and Western Ranges, AFSPC supported 23 successful military, civil, and commercial launches in 2007. The FY 2009 budget request supports sustainment and modernization of our launch ranges.
  - This year, AFSPC is deploying a new Air Force Satellite Control Network (AFSCN) antenna at Vandenberg Air Force Base which will facilitate over 30 satellite contacts per day. The AFSCN continues to be the Nation's backbone for satellite operations. AFSPC is upgrading antennas with the Remote Tracking Station (RTS) Block Change to ensure command and control of on-orbit capabilities is efficient and more accurate. The FY 2009 budget request funds the operation and gradual modernization of the AFSCN.

Increase space protection capabilities

The USAF and AFSPC play a key role in defending the Nation's military, intelligence, civil, and commercial space capabilities. The Air Force is uniquely charged with mission responsibilities to provide forces to defend United States space capabilities. Our strategy and investment approach balances the need for space situational awareness (SSA), protection of space capabilities and

protection of terrestrial forces from threats posed by adversary use of space against our interests.

- We must increase SSA while we address operational and physical vulnerabilities in our space, ground, and link segments. The challenge is to find an affordable pathway to protect space capabilities that strikes the right balance among awareness, hardening, countermeasures, reconstitution, and alternate means.
- The Integrated SSA (ISSA) program provides USSTRATCOM, Joint Functional Component Command for Space (JFCC-SPACE), and the joint community with an integrated source of current and predictive space events, threats, and space activities. By employing a near real-time, net-centric construct, AFSPC is achieving higher accuracy space surveillance through fusion of other SSA elements. Funding from the FY 2009 budget request increases our ability to characterize the space domain by focusing on space-event processing and analysis to include high-accuracy conjunction assessments and rapid-maneuver processing.
- AFSPC is also planning to field ground- and space-based sensors to improve space surveillance capabilities. The Space Fence program provides the capability to find, fix, and track small objects in low- and medium-Earth orbits (LEO and MEO) using three ground sites. The FY 2009 budget request for this program supports development awards to at least two contractors. Additionally, the Space-Based Space Surveillance (SBSS) program offers the ability to detect and track space objects; primarily those in GEO. With the FY 2009 budget request, AFSPC is completing development of SBSS Block 10, launching the satellite in FY 2009 and working toward development of SBSS Block 20.
- The Rapid Attack Identification Detection and Reporting System (RAIDRS) Block 10 program detects and geolocates satellite communications interference via fixed and transportable ground systems. In 2007, AFSPC activated the 16th Space Control Squadron at Peterson Air Force Base to operate RAIDRS and we deployed one system to the USCENTCOM Theater to protect over 400 SATCOM links. The FY 2009 budget request continues funding for the RAIDRS Block 20 update which is introducing an automated means to characterize anti-satellite (ASAT) and directed energy attacks on space systems and services.
- Building a comprehensive SSA picture includes a fully collaborative, net-centric space command and control architecture that links JFCC-SPACE to the joint fight. AFSPC improved our Nation's global space.
- AFSPC is committed to improving protection of ground, link, and space segments. While some of our space capabilities are well protected, AFSPC is taking into account that we will likely face a wider range of threats in the space domain and on the ground through links that control these systems. As we move forward to modernize and recapitalize, the nature of these threats means we are going to engineer space protection into our new systems.
- To help us make informed decisions about how best to preserve space capabilities, AFSPC is establishing the Space Protection Program. This program will focus our efforts and provide decision-makers with strategic recommendations on how to best protect our space systems and stay ahead of the threat. We are already strengthening and unifying relationships across the defense and intelligence community.

Attract, develop, and retain space professionals

While AFSPC is developing and wielding remarkable capabilities, the source of our tremendous accomplishments is our space professionals. Our challenge is to continue attracting, developing, and retaining Airmen with the skills necessary to maintain our competitive advantage. AFSPC is working with our partners in Air Education and Training Command (AETC), academia and elsewhere, to educate, train, and cultivate experts in the space domain who are both technically and tactically competent, and who are skilled in integrating with other warfighting domains.

- Since 1996, the United States Air Force Weapons School (USAFWS) has graduated 180 space instructors from a pool of AFSPC's best and brightest. Last year, AFSPC and the USAFWS continued their partnership in developing and delivering world-class graduates to expertly employ space and missile capabilities and to instruct the next generation of space operators.
- The tactical mindset is also evolving on the nuclear side. AFSPC is operating a world-class center focused on training nuclear security professionals. To ensure we are providing the most secure nuclear deterrent, 20 AF operates the Nuclear Space Security Tactics Training Center (NSSTTC) at Camp Guernsey, Wyoming. In 2007, this facility trained over 1,700 security forces on nuclear security and expeditionary tactics.
- AFSPC's National Security Space Institute (NSSI) is establishing itself as America's premier campus for superior space professional training and education. Last year, the NSSI taught 71 courses to 1,700 students—a 17 percent increase from 2006. Over 350 of those students were from other Services, and, for the first time, NSSI instructors taught our allied partners. In 2008, AFSPC is partnering more closely with Air University (AU) as it looks to transition more classes to AU in 2009.
- In 2007, AFSPC competitively selected 20 officer and enlisted space professionals for a fully funded University of Colorado at Colorado Springs (UCCS) Space Certificate pilot program, consisting of five courses focused on space and space systems, engineering management, information and communications systems, and space policy. This year, AFSPC is selecting its second class and is using this pilot program as a catalyst for a master's degree.

Sustain AFSPC's enduring missions and mature emerging missions

To better meet 21st century challenges, AFSPC will recapitalize its force to sustain enduring space force enhancement capabilities while designing a future force to ensure flexible, responsive capabilities in a contested domain. Fully recognizing we do not currently have a capability to perform maintenance or repairs on orbital assets, we are committed to protect and reinvigorate satellite constellations to provide the level of utility expected by users all over the globe. Additionally, AFSPC will work with appropriate government agencies to explore opportunities for enhanced commercial, allied, and international partnerships.

- *Transformational Satellite Communications System (TSAT).*

Since last year, the Joint Requirements Oversight Council (JROC) validated requirements for increased worldwide protected communications capabilities to extend the ground-based Global Information Grid (GIG) to deployed and mobile forces and to support Comm-on-The-Move, the Army's Future Force Initiatives, the Navy's ForceNet, and the Marine's X-Net warfighting visions. AFSPC is pursuing transformational communications capabilities and is studying a future MILSATCOM architecture investment strategy in response to Congressional direction to procure a fourth AEHF satellite. The FY 2009 budget request continues technology maturation and design of TSAT.

- *GPS III.* With GPS III, AFSPC is planning to further enhance military and civilian PNT capabilities by providing higher power, increased anti-jamming capability, and compatibility with European Galileo signals. By implementing a block approach, AFSPC will use the FY 2009 budget request for GPS III Block A development and preliminary design review, capability insertion for Blocks B and C, and risk reduction and concept development of the control segment.
- *Third-Generation Infrared Surveillance (3GIRS).* In addition, AFSPC is planning to continue the critical space-based infrared warning systems into its third generation. With the FY 2009 budget request, we will continue wide-field-of-view sensor testing and technology maturation activities along with development of an integrated test bed.
- *Upgraded Early Warning Radar (UEWR).* AFSPC is also embracing emerging missions such as missile defense. Last year, the UEWR program achieved several milestones when USSTRATCOM operationally accepted two UEWRs. As a key player in a recent Missile Defense Agency (MDA) flight test, the Beale UEWR and its crew acquired and tracked a flight-test target reentry vehicle launched from Alaska, enabling the successful destruction by an interceptor launched from Vandenberg Air Force Base. The FY 2009 budget request supports sustainment and operation of the Beale and Fylingdales UEWRs.
- *Operationally Responsive Space (ORS).* Last May, AFSPC successfully teamed with its sister services and interagency partners to stand up the ORS Office. AFSPC is working closely with the ORS Office to develop innovative acquisition approaches and capabilities to prepare the United States to respond to a contested space domain, to better respond to urgent warfighter needs, and to deploy small satellites and associated launch and control systems. AFSPC is continuing to work with the ORS Office to develop ORS as a national strategic capability and to export concepts to the broader Air Force space enterprise. The FY 2009 budget request supports the launch of TacSat-4 and continues the development of the first ORS spacecraft and enabling capabilities.

Improve the strategic acquisition, delivery, and sustainment of space capabilities

In today's world of rapid technological advancement and proliferation, we cannot afford to do business as usual when it comes to delivering space capabilities. We require a new strategy for how we develop, deliver, and sustain space systems that is more than an incremental progression of acquisition processes and management methods. Such a strategy requires a paradigm shift with an end-state that deploys needed space capabilities more quickly than in the past, while still executing efficient, business-like acquisition practices.

- To effect organizational and cultural changes, AFSPC is reviewing and adjusting its organization construct and processes. At the beginning of 2008, we reorganized Headquarters AFSPC activities, functions, and relationships to enhance our ability to act as a single, integrated organization.
- Our next step is fostering external relationships. AFSPC is clearly articulating the need for science and technology, research and development, acquisition, sustainment, and training to Air Force Materiel Command (AFMC) and AETC. We are also intensifying collaboration with Air Combat Command (ACC), including the USAF Warfare Center (USAFWC). Furthermore, AFSPC is supporting other major commands with space expertise and analysis.
- We are also working on proper alignment of development, acquisition, and sustainment activities. We continue to build a more powerful and effective partnership with AFMC and SMC through better definition of roles, responsibilities, and authorities.
- Finally, we have chartered a special study group to examine alternative acquisition strategies and recommend ways to shorten the time it takes to put space capabilities in the hands of the warfighter.

Improve integration across the air, space, and cyberspace domains

Integration across air, space, and cyberspace is more than combining and disseminating data among interrelated architectures. If air, space, and cyberspace power each have a value of one, the sum of these capabilities is far greater than three. AFSPC is working with the other Air Force major commands and domain experts to develop shared strategic plans, operational concepts and architectures, doctrine, as well as tactics, techniques, and procedures for the next conflict—one where emerging technologies in air, space, and cyberspace domains can be leveraged and mutually supported within a joint construct.

- AFSPC is teaming extensively with the USAFWC and USSTRATCOM to increase space scenarios across the full spectrum of exercises. In March 2007, AFSPC conducted the most comprehensive space wargame to date with 470 participants, including 74 flag officers or equivalents and 38 allied partners. This wargame focused on the future and explored global space system architectures, technologies, and C2 relationships; tackled concepts for integrating space with other warfighting domains; and examined potential policy trends and their implications. We look forward to the next game in 2009.

Conclusion

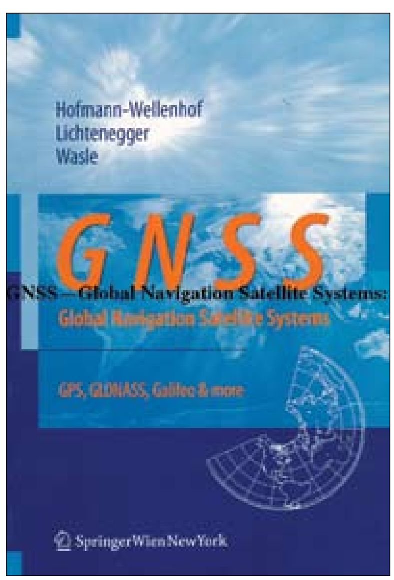
The Total Force AFSPC team plays an important role in delivering space and missile capabilities to America and its warfighting commands. These capabilities provide a decisive advantage for our national security and prosperity. With the continued support of the Congress, AFSPC is postured to continue to maintain a crucial leadership role as we realize our vision of *delivering responsive, assured, and decisive space power.*

GNSS—Global Navigation Satellite Systems: GPS, GLONASS, Galileo, and more

GNSS—Global Navigation Satellite Systems: GPS, GLONASS, Galileo, & more. By Bernhard Hofmann-Wellenhof, Herbert Lichtenegger, and Elmar Wasle. New York: Springer-Verlag Wien, 2008. Figures. Tables. List of Abbreviations. Bibliography. Index. Pp. xxix, 516. $79.95 Paperback ISBN: 3211730125.

An extension of Bernhard Hofmann-Wellenhof's bestselling *GPS—Theory and Practice*, which appeared in 1992 and went through five editions within a dozen years, *GNSS—Global Navigation Satellite Systems* follows the contours of that earlier work across a broader field of view. Like its predecessor, this new volume is described by the authors as a "university-level introductory textbook," but they might have been more accurate if they had labeled it as best suited for intermediate-to-advanced classroom use. Also, like the earlier book, this one is intended to serve as a reference for students, scientists, and professionals "in the fields of geodesy, surveying engineering, and navigation, and related disciplines." The authors, all specialists in geodesy with academic connections to Austria's Graz University of Technology, stress that their backgrounds might cause geodetic perspectives sometimes to dominate this introduction to GNSS theory.

Primary author Hofmann-Wellenhof has crafted a brilliantly succinct discussion in the book's foreword on the meaning of "Global Navigation Satellite System" and "GNSS," its abbreviation. He focuses on usage, in singular and plural form, of the word "system." At present, from his perspective, the US GPS and the Russian GLONASS each comprises a separate GNSS; once developed and deployed, systems like the European Galileo, Chinese Beidou, and Indian IRNSS each will be a GNSS. To the extent that these several GNSSs achieve compatibility and interoperability, they constitute a single GNSS that offers better performance at the user level than does any one of the GNSSs by itself. Sticking as much as possible to GNSS in the "generic sense," Hofmann-Wellenhof and his fellow authors describe "various reference systems, satellite orbits, satellite signals, observables, mathematical models for positioning, data processing, and data transformation" in a veritable tour de force.



The result amounts to 14 intellectually challenging chapters. These begin with a historical review of the origins of surveying and the development of global surveying techniques. They conclude with the future of GNSS and how users might benefit from the ongoing development. Sandwiched between these thin slices are thick, meaty portions on the seven topical areas mentioned in the previous paragraph, each heavily peppered with mathematical formulas and a healthy sprinkling of online source materials. To complete their menu, the authors offer a dessert tray of five, richly flavored chapters on GPS, GLONASS, Galileo, other systems, and some GNSS applications. Each chapter on a specific system contains layers of information on its history, project phases, management and operation, reference systems, services, segments, signal structure, and outlook. Readers can also sink their teeth into tastefully prepared subsections on what the authors characterize as global, regional, differential, augmentation, and assistance systems. Finally, for those who remain unsatiated after finishing this book, nearly thirty pages of bibliographic material serve as a guide to other, potentially delectable morsels.

This book might disappoint those who expect to find detailed coverage of certain aspects of GNSS. We still await a book-length, scholarly history on the development of GPS and its experimental precursors. From a military standpoint, some might label *The Precision Revolution: GPS and the Future of Aerial Warfare* (Annapolis, Maryland: Naval Institute Press, 2002) by Michael Russell Rip and James M. Hasik a small step in that direction, but much research and writing remains unaccomplished. As for GNSS applications, this reviewer's "NAVSTAR, the Global Positioning System: A Sampling of Its Military, Civil, and Commercial Impact," a chapter in the recently published *Societal Impact of Spaceflight* (Washington, DC: NASA, 2007) by editors Steven J. Dick and Roger D. Launius, could prove more satisfying than what appears in *GNSS—Global Navigation Satellite Systems*. In terms intelligible to the vast majority of people, parts of the GNSS story have thus far appeared only as snippets in popular magazines and trade journals or online at websites like *GPS World* and *Inside GNSS*.

Before you rush to purchase *GNSS—Global Navigation Satellite Systems*, heed the following words of caution. Intellectually lazy readers could find themselves gasping for breath by the end of the first chapter, and the inattentive will be sinking into textual quicksand before the end of the second chapter. The mathematically challenged will abandon all hope of understanding when they confront page after page of complicated equations. Even some who possess a solid grounding in trigonometry, linear algebra, and basic calculus might protest as their brains undergo synaptic strain. This is not a book for someone seeking basic knowledge about how GNSS operates and what its applications might be. For those requiring a rigorous introduction to the theories underpinning GNSS, however, this volume is the place to start.

Reviewed by Dr. Rick W. Sturdevant, deputy command historian, HQ Air Force Space Command.

We are interested in what you think of the ***High Frontier*** Journal, and request your feedback. We want to make this a useful product to each and every one of you, as we move forward to professionally develop Air Force Space Command's space and missile workforce and stimulate thought across the broader National Space Enterprise. Please send your comments, inquiries, and article submissions to: HQ AFSPC/PA, High Frontier Journal, 150 Vandenberg St, Ste 1105, Peterson AFB, CO 80914-4020, Telephone: (719) 554-3731, Fax: (719) 554-6013, Email: afspc.pai@peterson.af.mil, To subscribe: hard copy, nsage@colsa.com or digital copy, http://www.af.mil/subscribe.

U.S. AIR FORCE

AIR FORCE SPACE COMMAND

AFSPC/PA
150 Vandenberg St.
Ste 1105
Peterson AFB, CO 80914
Telephone: (719) 554-3731
Fax: (719) 554-6013
For more information on space professional development visit:
www.peterson.af.mil/spacepro

Air & Space Power Journal:
www.airpower.maxwell.af.mil/airchronicles/apje.html